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# Portable Unmanned Aircraft System Concept Investigation

*Keith Cameron and Victor Kowalenko*

**Aeronautical and Maritime Research Laboratory**
**Air Operations Division**

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## ABSTRACT

This report investigates the feasibility of a portable unmanned aircraft system (PUMA) for deployment in various close range (up to 30 km) reconnaissance and surveillance missions, which would provide a capability, estimated to be 50 to 60% of the performance of much larger and significantly more expensive sytems. The PUMA would have a total mass of 10-12 kg and a 3 kg electrically powered flying wing configuration, which could be launched by a rubber bungee and captured by either a net or a special arrestor. The primary sensor would be a charge coupled device camera with either a second or third generation image intensifier. Navigation and control of the vehicle could be performed by an inexpensive attitude and heading reference system combined with a small global positioning system receiver. Data would be transmitted over very high frequency channels, which could be accomplished by employing data compression techniques.

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# Portable Unmanned Aircraft System Concept Investigation

## EXECUTIVE SUMMARY


The aim of this report is to investigate the feasibility of a Portable UnManned Aircraft System (PUMA) in order to enhance current reconnaissance and surveillance capabilities within the Australian Defence Force. Specifically, this report deals with the feasibilility of a system with the following capabilities:

(a) a radius of action up to 30 km at altitudes of up to 1 km above local ground level;
(b) transportable by 'Landrover' type vehicles;
(c) electric powered so as to minimise acoustic, heat and vibration signatures;
(d) suitable for operation at night.

In this report we examine and evaluate developments in unmanned aircraft systems, paying special attention to the various subsystem technologies such as the sensor payload, launch and recovery methods, propulsion systems, air vehicle designs and navigational and control systems. We also indicate which operations are currently being carried out by the ADF that would benefit most from the deployment of a PUMA. In particular, we direct our study at reconnaissance operations conducted by Regional Force Surveillance Units and other land-based patrols, surveillance operations in the protection of vital assets and the surveillance operations of patrol boats in the sea-air gap.

Based on our study of subsystem technologies, the recommended PUMA vehicle would be a slightly swept flying wing constructed of a composite such as epoxy kevlar. It would have a total mass up to 12 kg with a wing span of about 3.6 m and would be propelled by a rare-earth electric motor connected to an energy source comprised of either primary lithium sulphur dioxide batteries or aluminium-air fuel cells. The airspeed of this vehicle is estimated to range from 20 to 70 kn. A primary sensor payload consisting of a charge coupled device camera connected to either a second or a third generation image intensifier could operate at light levels down to clear starlit nights. Navigation and control of the vehicle could be achieved by an inexpensive attitude and heading reference system consisting of two or three solid state gyroscopes, an altimeter, a magnetometer and an airspeed sensor combined with a small global positioning receiver. Data compression techniques, of which the discrete transform technique offers the highest compression ratios in addition to a real-time capability, would be required to transmit data from the sensor payload over high or very high frequency channels to a ground control station in the form of a laptop computer. On return from a mission, the vehicle could be retrieved by a recovery net for land-based operations and in the case of naval operations, it could be captured by a special arrestor system attached to a ship's rail as described herein.

The Defence value of this work is a greater understanding of the capabilities and limitations of small unmanned aircraft for surveillance.

# Authors

## Keith Cameron
### Air Operations Division

Keith Cameron obtained a B.Sc. (Hons.) in aeronautical engineering from the City University of Technology while working for the UK Defence Department. He then studied at the Cranfield Institute of Technology and was awarded a M.Sc. in aerodynamics in 1975. Returning to Australia in 1975, he joined the Department of Transport's Flying Unit as a flight operations engineer. He moved to the then Aeronautical Research Laboratory (ARL) in 1976 to participate in remotely piloted aircraft development. During his time at ARL, now part of AMRL, he has worked on systems aspects of a number of projects including Ikara and Nulka. This work has included aerodynamic testing, development of data acquisition systems, autopilot development, trials and studies at both systems and operational levels. He is currently working in the area of instrumentation and data acquisition systems for aircraft trials and wind tunnels.

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## Victor Kowalenko
### Air Operations Division

Victor Kowalenko graduated with a B.Sc. (Hons) in physics from the University of Melbourne in 1978. Awarded a Commonwealth Post-Graduate Research Award he undertook a Ph. D. in theoretical quantum plasma physics at the same university, completing it in 1982. Thereafter he joined the former Materials Research Laboratories to carry out research into the theoretical plasma physics of the railgun project. In 1987 he moved to the Aeronautical Research Laboratory, now part of AMRL, to undertake research into aircraft systems and remotely piloted vehicles. Between 1991 and 1994, he was on leave taking up one of the inaugural and highly prestigious Australian Research Fellowships at the University of Melbourne where he undertook research into the role of quantum plasmas in astrophysics and in general relativistic magnetohydrodynamics. Since his return to Air Operations Division at AMRL, he has been involved in employing operational research models to simulate military scenarios. Dr Kowalenko also has research interests in various fields of applied mathematics including asymptotics, mathematical methods and classical analysis.

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# Contents

# 1. Introduction

Australia's defence strategy is based on the concept of depth in defence, which gives the Australian Defence Force (ADF) a priority to mount maritime and air operations capable of overcoming enemy forces in the sea and air gap north of Australia and to employ mobile land forces to defeat hostile incursions [1,2]. Many of the tasks associated with carrying out this strategy involve reconnaissance and surveillance operations. Currently, these operations are carried out by satellites, aircraft and land and sea patrols over the vast area within the Australian Fisheries Zone as indicated in Fig. 1. However, there are many instances where the deployment of UnManned Aircraft systems (UMAs) or Unmanned Aerial Vehicles (UAVs) in these operations could enhance present capabilities. In this report we aim to investigate specifically the feasibility of a Portable UnManned Aircraft system (PUMA), which could be deployed in specific operations that fall under the concept of defence in depth, viz. the reconnaissance operations of small land-based units and the surveillance operations of patrol boats in the sea-air gap.

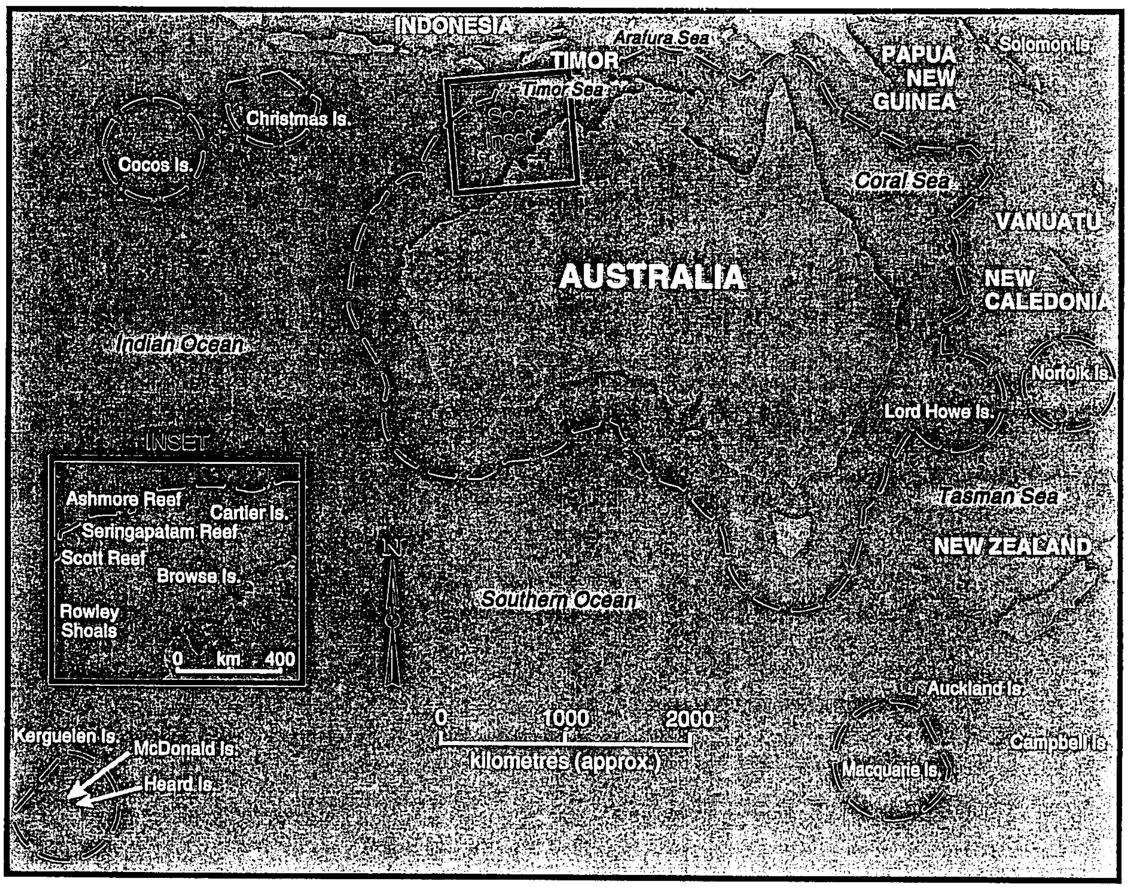


*Figure 1: Australia and the Australian Fisheries Zone*

In this report we shall refer to reconnaissance as the collection of information either about the activities and resources of an enemy or about the climatic and geographic characteristics of a particular area, while surveillance is defined as the systematic observation of aerospace, surface or subsurface areas, places, people or objects by visual, aural, electronic, photographic or other means.

There have been numerous designs proposed for UMAs over the past two decades, but few have become operational. Many systems have become too large and sophisticated as the original capabilities have been extended leading to increased development costs and operational support requirements. The cancelled US Aquila program [3-5] is the most well-known example. However, fundamental changes or advances have occurred in UMA technology since the early 1970s resulting in decreasing mass, size, power consumption and cost. As a consequence, small UMAs are becoming increasingly capable. They are also very difficult to detect and destroy.

The Israeli success with the Mazlat 'Mastiff' and 'Scout' Remotely Piloted Vehicles (RPVs) demonstrated that small UMA systems can perform useful missions and that the Ground Control Station (GCS) and its communication link are important elements in the UMA system. Initially, field commanders thought that the Mastiff with its basic 'flying camera' system was just a toy, but the value of real-time imagery the system provided in a military engagement soon became apparent [6].

Aside from examining scenarios where a portable UMA could be beneficial to current ADF operations, we also investigate the current state of the art in the various subsystem technologies required in the development of the PUMA. Whilst the proposed PUMA has limited reconnaissance and surveillance capabilities, many of the technological aspects discussed in this report are relevant to all UMA systems. In addition, it should be noted that by concentrating on key requirements as indicated in Ref. [7], the proposed PUMA is both very simple and very affordable.

# 2. Puma Missions for the ADF

The military use of UMAs has been led by Israel, which has used simple short range UMAs to gather information and operate as decoys over at least the past decade. UMAs have served effectively in a complementary role by supporting Israeli manned-aircraft operations, for example in conducting reconnaissance and decoy missions [8] followed by battle damage assessment [6] against Syrian Surface to Air Missile (SAM) installations.

Arguments to support UMAs, particularly close-range ones [9] are as follows; the cost of UMA development, acquisition and operation is much less than that for an equally capable manned aircraft, while mission-effectiveness and survivability may also be superior to manned aircraft. In heavily defended areas the high risk to manned aircraft and rate of aircrew loss undermines mission effectiveness over sustained operating periods and losses can rapidly escalate to unacceptable levels. The comparatively small UMA powerplant and low radar reflectance of typical airframes yield commensurately small thermal, radar and visual signatures, which frustrate infrared (IR) seeking missiles and radar-controlled guns. Thus UMAs are inherently stealthy.

## 2.1. Army Operations

Intelligence has become a prime requirement for the success of low-level operations. Regional Force Surveillance Units (RFSUs), Army aviation reconnaissance units and reconnaissance patrols are deployed on surveillance and reconnaissance tasks to gain timely information in order to support land force elements conducting protective or reactive operations [10]. The deployment of a PUMA can assist these land units by providing much of this valuable information, thereby enhancing available manoeuvre options [11].

To illustrate the above, some major lessons learnt from the Kangaroo 89 Exercise (K89) [12] were :

- The surveillance effort required the commitment of a significant number of assets which may not be available throughout protracted operations;

- The requirement for Army reconnaissance aircraft with up-to-date sensors, improved range and performance, as well as enhanced survivability was clearly demonstrated.

In K89, reconnaissance operations for supporting land forces were conducted with Kiowa and Black Hawk helicopters. Helicopters are expensive to operate, easy to detect, vulnerable to counter measures (such as Stinger type missiles) and may not be available or worth risking when required for reconnaissance tasks.

The three RFSUs (Norforce, the Far North Queensland and Pilbara Regiments) are potential users of PUMA systems. These units patrol northern Australia (including the rivers in 'Zodiac' craft [2]). A PUMA has the potential to enhance the reconnaissance capability of these three units significantly, not only by assisting in the observation of dense vegetation near river banks but by extending the observed area for these river patrols well beyond the river banks.

Scouting and patrolling are particularly hazardous operations in a combat zone [9]. A PUMA has the potential to reduce the risk and the time required for these missions, thereby acting as a force multiplier for these tactical missions. Specific scenarios where the deployment of a PUMA could enhance present capabilities include:

(a) inspection of possible ambush sites, e.g. looking over the next hill for enemy forces;

(b) covering areas of potential enemy fire when crossing danger areas;

(c) inspecting stream and road crossings for difficulties;

(d) looking for routes through difficult terrain and around obstructions;

(e) generally extending the 'foot print' of the patrol.

These scenarios are depicted in Figs 2-5.

A close-range UMA has also the potential to assist in the protection of vital assets/installations (PVA) such as airfields. Surveillance of airfield perimeters is currently conducted by the Army Reserve [13]. One of the major lessons learnt from the K89 exercise was that tasks associated with PVA require considerable resources and that Army Reservists need greater mobility, intrusion sensors and enhanced fire support systems to be fully effective [12]. A PUMA with a range of 10 km and flying up to 1,000 m above ground level would be of great benefit in PVA missions. Furthermore, since the system would operate over a known area, it would not require a sophisticated navigation system.

## 2.2. Naval Operations

Surveillance and patrol operations in the sea-air gap north of Australia are of fundamental importance to the concept of depth in defence [1,2]. Although surveillance is almost as important as intelligence in ensuring that an enemy is detected in time to deliver an appropriate response, small shallow draft boats can sail undetected between the numerous islands in the Torres Strait, especially at night [14], thereby exposing a deficiency in the current strategy of depth in defence. A close range UMA operating from the islands, however, could provide a covert and cost effective method of monitoring this area.

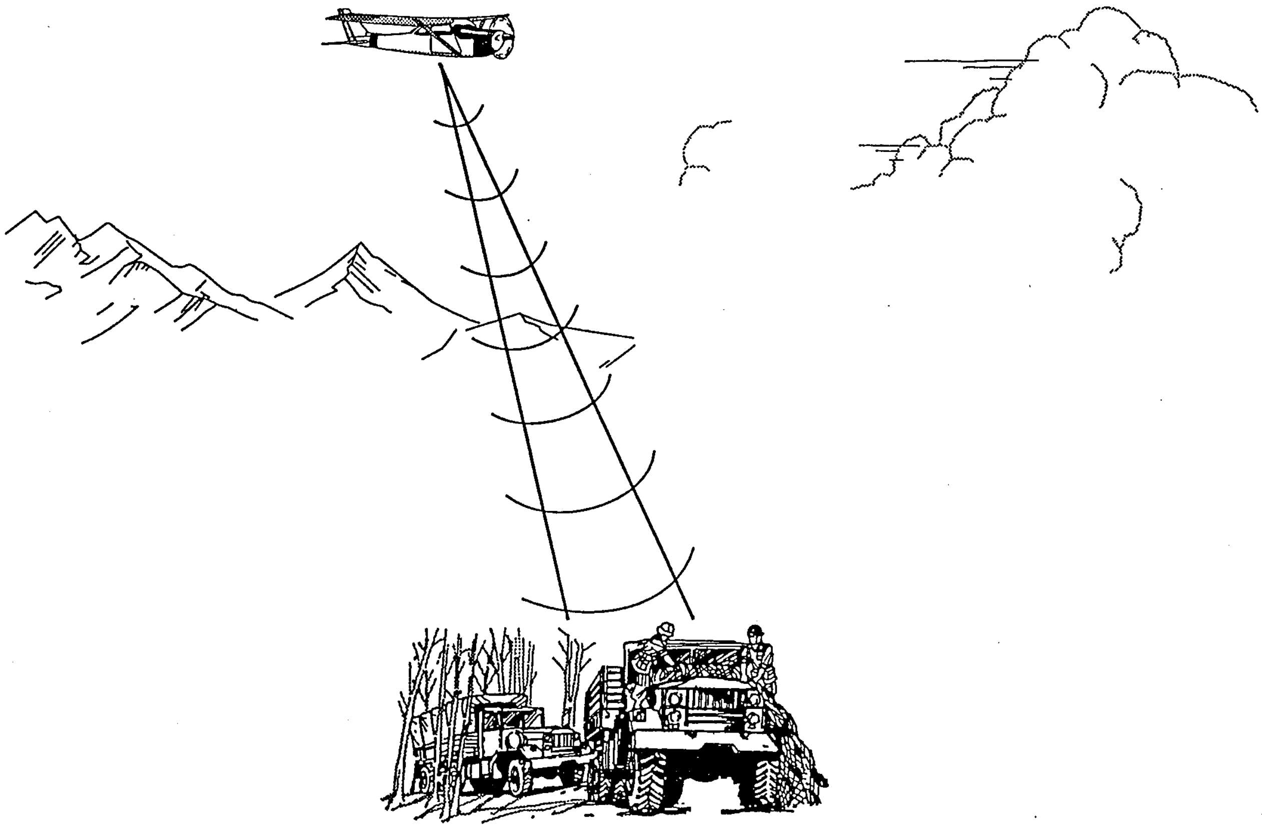

*Figure 2: Typical Application - Monitoring of People/Vehicle Activities*

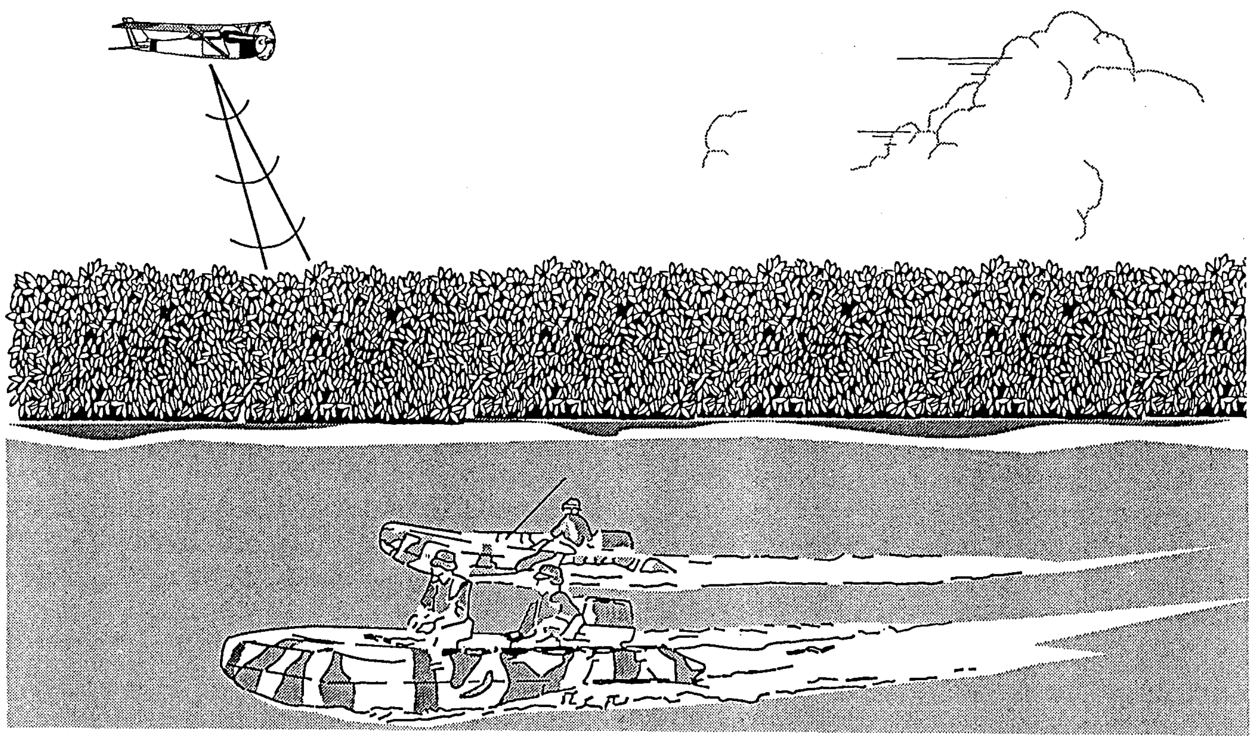

*Figure 3: Typical Application - River Patrol*

*Figure 4: Typical Application - Looking for Paths through Difficult Terrain*

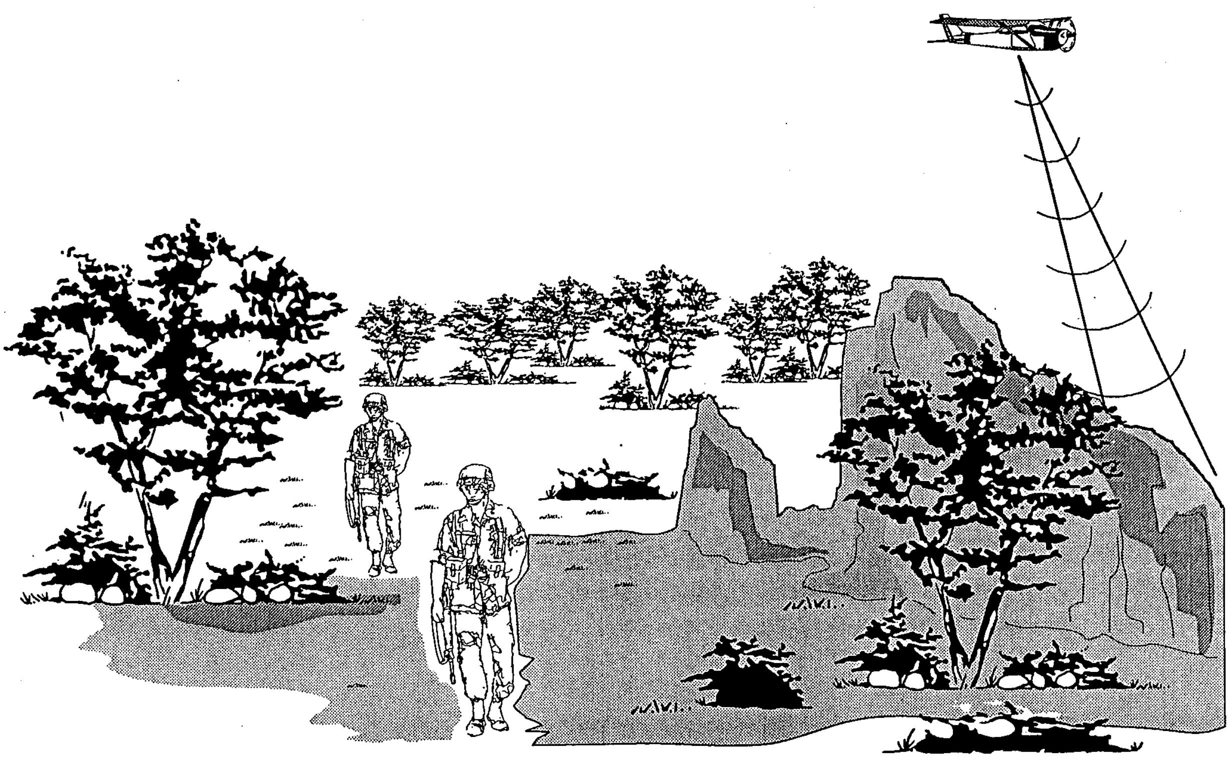

*Figure 5: Typical Application - Area Surveillance/Reconnaissance*

The maritime exercises report for K89 [15] also emphasised the deficiencies in current ADF surveillance capabilities, by declaring that the number of surveillance assets, which consisted of the majority of available ADF assets supplemented by US aircraft, Coastwatch and Jindalee, was generally insufficient for the task and that this was not surprising in view of the magnitude of the surveillance task and paucity of ADF assets. The patrol boats of the Orange forces, in particular, were often able to avoid detection for extended periods. The lack of assets also led to tasking conflicts and priority could not always be allocated to surveillance tasking.

Factors affecting the detection capabilities of surveillance craft [13] are:

(i) environmental conditions, such as sea state and climate;

(ii) target characteristics including the size, speed, construction material and aspect relative to the surveillance aircraft;

(iii) observer performance;

(iv) target range.

Typical visual detection ranges of fishing trawlers and small merchant vessels at sea are five and eight nautical miles respectively. A close range UMA on a patrol boat may extend these detection ranges considerably and more importantly provide a means to identify detected vessels possibly by reading their identification numbers. This would relieve the patrol boat of the need to close with each detected vessel (there may be multiple vessels either in view or on radar at any one time) thereby enhancing the efficiency of patrol boat operations. As these systems are relatively inexpensive, more than one vehicle could be deployed at the same time, although the actual number of vehicles would be dependent on the number of available personnel. These systems could also be deployed to conduct surveillance operations in areas inaccessible to patrol boats such as coastlines and river estuaries.

The US Coast Guard has indicated the need for a close-range UMA in its operations [16] with the following system requirements and capabilities:

(a) video resolution such that 150 mm (6 in) high letters could be read at 30 m or the minimum legal distance aircraft must maintain from surface craft in international waters;

(b) range of at least 18 km (10 nmiles);

(c) two hour endurance at 40 kn and a minimum ceiling of 90 m (300 ft);

(d) UMA mass not to exceed 72 kg;

(e) no specialized UMA knowledge required by the operator;

(f) minimal storage-to-launch and recovery-to-stowage times; not to exceed 1 hr each (2 hr for the latter in wet conditions);

(g) minimal system size with no linear container length to exceed 2.4 m (8 ft);

(h) minimal control station mass.

Such a UMA is expected to be more cost-effective than a helicopter and allow Coast Guard cutters (approximately the size of frigates) to identify nearby ships without altering course. A system meeting the above requirements might also be small enough to be deployed from RAN patrol boats.

A close-range UMA could be deployed in missions to enhance protracted surveillance operations being conducted by helicopters off surface ships and patrol boats. For example, ship launched UAVs may be a viable alternative to surveillance by ship based helicopters, particularly when the identification of craft is necessary. The deployment of close-range UAVs to conduct these surveillance operations within 30 km and short range UAVs for operations up to 150 km would also be more cost-effective than deploying helicopters. Furthermore, a close-range UMA could be deployed first to establish the key requirements and the system capabilities for the deployment of the much more sophisticated and expensive short range UMAs, whose radii of action can extend to 150 km with flight endurances between 5-12 hr.

# 3. UMA System

A UMA system consists of the flight vehicle with various subsystems, which include the sensor payload, the propulsion system, the navigation and control system in addition to a ground control station (GCS). Other aspects that need to be considered for the deployment of these systems are the launch and recovery methods and the data link enabling the transmission of sensor data to the GCS. A UMA system depicting how the various subsystem technologies are interrelated is given in Fig. 6 while Fig. 7 shows how the entire PUMA would be deployed in a mission.

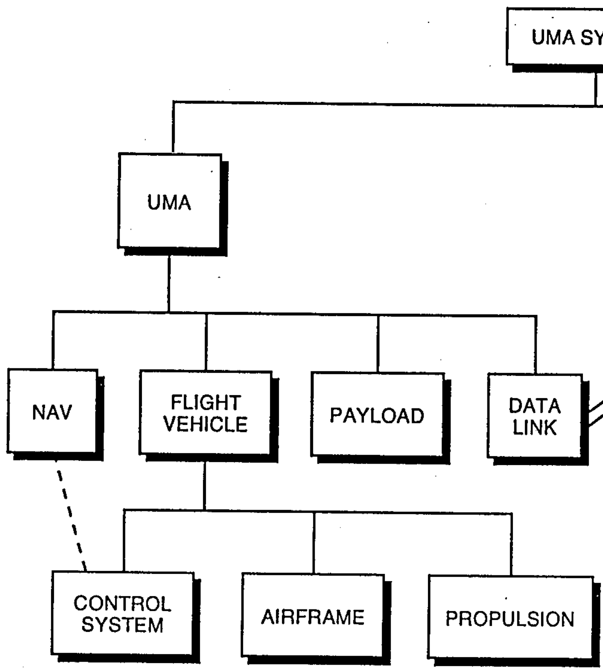


*Figure 6: Subsystem Technologies*

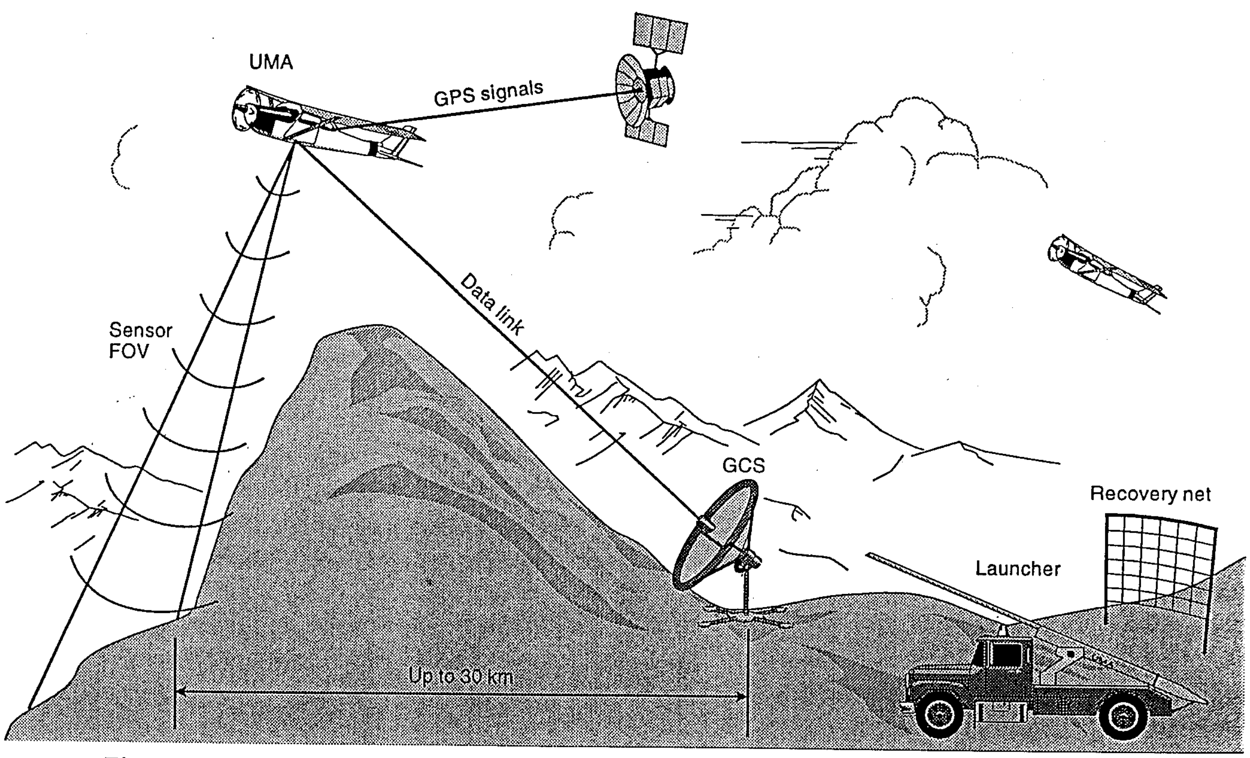


*Figure 7: Typical Operation*

## 3.1. Sensor Payload

Since the PUMA vehicle is to be as small and as light as possible, it cannot carry sensor packages such as the current forward looking infra-red (FLIRs) and infra-red (IR) line-scan imagers that are carried by larger UAVs. As a consequence, the sensor payload for the PUMA must be restricted to daylight and/or low light imaging sensors based on charge coupled device (CCD) technology. IR sensors detect the radiation emitted by bodies due to their temperature while video sensors detect the radiation reflected from an object. IR CCD cameras have one major disadvantage in that they require cooling to cryogenic temperatures and the UAV would need to carry a cooling system. Image intensifiers do not require cooling, but do not have as good a 24hr performance as that of an IR CCD camera.

The simplest type of sensor that the PUMA could carry is a black and white (monochrome) CCD camera with a fixed viewing direction relative to the airframe. CCD cameras are suitable for daytime operations and combined with an image intensifier can be used on clear starlit nights [17]. The combination of a visual CCD camera with an image intensifier should, therefore, be able to provide a partial night time capability in a sensor package that is compatible with the PUMA concept.

There are several areas where developments in technology may lead to lightweight FLIR type sensors suitable for a PUMA. These are the combination of PtSi Schottky barrier photodiode technology with proven CCD imager technology, IR CCD cameras and pyroelectric thermal TV cameras. However, at present there is no single sensor payload weighing less than 2.5 kg that possesses an all-weather night-time capability, though significant advances have been made in the development of IR CCD cameras utilising PtSi staring focal plane arrays. These systems, which operate in the medium wave infra-red (MWIR) band of the electromagnetic spectrum, have already exceeded the performance of traditional scanning FLIR imagers operating in either the long wave infra-red, MWIR or short wave infra-red bands. Nevertheless, they are still too heavy and bulky for a PUMA. Future miniature cooling devices weighing about 1 kg may lead to the production of a thermal imaging device weighing only 3 kg. A basic CCD camera weighs about 0.5 kg and though capable of providing good resolution, it is restricted to daytime operations. A partial night-time capability can be achieved by combining an image intensifier with this camera. A good CCD camera has a current retail value of about $2 K while a 2nd generation image intensifier costs about $4 K. The combined system known as a Gen II device is significantly cheaper than a thermal imager.

Image intensifiers are currently the most widely deployed night-vision technology, particularly with the advent of third generation or Generation III devices [18]. Gen III tubes, which employ gallium arsenide technology, have several advantages over Gen II designs. They are more efficient, which means that the effective range of surveillance devices and weapon sights can be doubled and their near IR response matches the night-sky irradiance better. Although more expensive, they also have a longer operating life. From a brochure of a few years ago [19], Fairchild Weston was developing its Gen III system, which was expected to weigh only 1.3 kg, to have a

length and a width of 10.2 and 5.6 cm respectively, and to be capable of producing 30 frames/s. Such a device when coupled to a CCD camera could be deployed as the primary sensor in the PUMA and would extend visibility to clear starlit nights. Not only are current intensified CCDs (ICCDs) significantly cheaper than thermal imagers, they are smaller and lighter as well as perform better than their second generation predecessors. This is not only a consequence of the expanded bandwidth of the Gen III tubes but also the increased pixel density of current CCD arrays [20].

Ideally an imaging sensor should be both steerable and stabilised, but given the size constraints of the PUMA, this is not possible. However, the ability to steer the sensor is almost essential as it is very frustrating to loose sight of an object due to limitations in flight vehicle manoeuvrability. In addition, search times can be drastically reduced if the sensor can be panned to see objects not on the line of flight. Steerability can be achieved for a very much lower mass than stabilisation and should be incorporated in the sensor payload. The stabilisation requirement can be addressed by minimising vibration levels in the flight vehicle and by image processing at the GCS.

## 3.2. Propulsion System

Traditionally UMAs have relied on a propulsion system belonging to one of two categories: propeller-driven or jet/rocket driven. Included in the first category are piston engines (2-stroke, 4-stroke, rotary and Stirling engines) and turboprops. Examples of the second category include turbojets, fan jets, pulse jets, ramjets and rocket ramjets [21]. Jet and rocket engines are in general not suitable for the low speed and long duration requirements of a reconnaissance/surveillance mission and though cheap, they are fuel-inefficient, extremely noisy and produce a high level of vibration. Thus, the second category of propulsion system can be ruled out for the PUMA.

Although some of the major problems with rotary engines such as high fuel consumption, inefficiency due to insufficient combustion and inadequate reliability have been overcome in recent years with the advent of the Norton P73 engine [22], it is unlikely that a scaled-down version to below one kg for deployment in the PUMA vehicle will become available. This leaves small piston engines either 2 stroke or four stoke as the only viable IC engines. However, with the major advances occurring in battery technology over the last decade electric propulsion has also become a viable means of propulsion, particularly for close range missions. To convince the reader of the viability of electric propulsion for UMAs, we present the following examples:

- in mid-November 1988, Quiet Air Inc. of San Diego, Ca. in conjunction with Westinghouse Oceanic Div., Cleveland, Ohio flew their Low Observable Electric UAV for 1 hr at 600 m (2000 ft) [23]. This UAV, which weighed between 7 and 10.5 kg (payload of up to 3.5 kg), was 1.5 m long with a wing-span of 3.5 m. Control was achieved by a 2 axis autopilot and a microprocessor from which various sensor payloads including a forward looking IR (FLIR) sensor and a jammer could also be run;

- a slightly larger UAV is the prototype built by Alupower Canada Ltd of Kingston, Ontario [24], which has a potential range of 64 km at a speed of 37 km/h. This vehicle is constructed of a mylar aluminium composite, and is 3.5 m long with a wing-span of 5.5 m. The 3.1 sq m wing has an aspect ratio of 9.8. The empty mass is 5.4 kg and maximum mass 9.1 kg.

Because proposing an electric propulsion system represents a departure from conventional UMA technology, we present here a detailed discussion of the relative merits of an electric powered propulsion system over a fuel powered system.

As a consequence of the close range of its missions and its small size, there are really only two viable propulsion systems for the PUMA, the IC engine and the electric motor. With regard to the former, most UMAs (about 60%) use some form of 2-stroke piston engine [25]. In general, 4-stroke engines are heavier by as much as 20% and are more expensive to produce than their 2-stroke counterparts (for the same power output) but they are easier to start, have a better power to volume ratio and consume less fuel. These features, however, have little bearing on the selection of a particular IC engine for a PUMA because of the small size of the entire propulsion system. 4-stroke engines are marginally less noisy, but they produce significantly more vibrations than 2-stroke engines, which hamper the performance of the sensor payload. As a consequence, the choice of IC engine can be further narrowed so that the remainder of this section is devoted to a detailed discussion of the relative merits of the 2-stroke IC engine and the electric motor as the two most favoured means of propulsion for the PUMA.

The appropriate propulsion system for a UMA depends on a large number of factors, which vary in importance depending on the mission requirements. For example, electrical power is not appropriate for medium to long range missions because the energy density of batteries is significantly lower than that of hydrocarbon fuels. Thus, even though electrically powered vehicles are much quieter than their fuel powered counterparts, they do not have the necessary endurance for long range missions. For such missions, the selection of an appropriate fuel powered system such as a 2-stroke, 4-stroke or jet engine is influenced by additional mission requirements. For example, if the mission requirements are that the vehicle reaches its destination as quickly as possible and has low vibration levels, then the appropriate propulsion system is a gas turbine engine. On the other hand, if the UMA is to conduct a close to short range reconnaissance mission where the primary requirements are for a silent propulsion system with minimal thermal signature and vibration, then an electrically powered system may be appropriate. A limiting case might be a tethered aircraft for which the power to stay aloft is transmitted via the cable or is supplied by the wind, as in the case of kites and tethered gliders. As an aside, German U-boats in WW2 used a man carrying tethered autogyro for look out purposes. As a general rule, range, speed and endurance are the most important factors in the selection of a propulsion system while mission/operational requirements affect the detailed design/specifications of the chosen system [26].

The performance factors affecting the selection of an appropriate propulsion system [26,27] include:

- reliability, which affects how many UAV missions may be conducted without failure;
- fuel efficiency, which is a measure of the vehicle's endurance or range rated against its fuel load;
- energy to mass ratio, which is critical in setting a limit on the endurance and range of the UAV;
- power to volume or diameter ratio, which affects the aerodynamic efficiency of the vehicle since the greater the volume or frontal area of the engine/motor, the greater the vehicle drag.
- fuel energy to volume ratio;
- size and mass of the vehicle and its payload.

The mass and volume parameters appearing in the above ratios refer to the combination of engine and fuel load. The choice between heavy efficient and light inefficient engines is primarily determined by the mission requirements. Other factors to be considered when choosing a power plant are:

(a) noise levels;

(b) IR signature;

(c) vibration levels;

(d) pre-flight preparation requirements;

(e) level of safety in launch and recovery;

(f) need for cooling;

(g) flight control;

(h) cost and availability.

For an electric powered vehicle, criterion (g) also includes the capability of the vehicle to switch its engine on and off during flight. Thus, when approaching objects of interest, these vehicles would be able to become completely silent, and to minimise vibration, the latter improving the image quality (a couple of minutes gliding would loose around 500 feet in altitude). In addition, the reliability of electrically powered vehicles in starting instantly is a factor impacting on criterion (d).

A fuel powered propulsion system for a PUMA would consist of:

(i) a 2-stroke IC engine including carburettor weighing approximately 300 g;

(ii) a 50 g actuator for throttling the engine;

(iii) a fuel pump, tank and lines with a total mass of about 100 g;

(iv) an exhaust system weighing about 100 g;

(v) an ignition system also weighing 100 g;

(vi) a propeller weighing between 100 and 200 g;

(vii) 20 g of ducting/cowling to facilitate cooling of the engine.

Small IC engines are not very fuel efficient [28] and for a UMA requiring 300 W with a fuel consumption rate of 0.6 kg/Whr (1 lb/hp-hr), 180 g of fuel would be needed for each hour of flight. Thus for a 1 hr flight endurance, the total mass of the IC propulsion system for the PUMA would be 1.0 kg with 0.18 kg required for each extra hour. In addition, electric power will still be required to power other systems in the vehicle such as the sensor payload, the data link and the navigation and control system. This power can either be provided by supplementary batteries or by an alternator/generator attached to the engine both of which increase vehicle mass.

An electric propulsion system is simpler to construct than the typical IC engine propulsion system. Typically, for a close-range vehicle such as the PUMA, the electric propulsion system would consist of batteries or fuel cells, a brushless permanent magnet electric motor, a propeller, a controller or switching electronics to regulate the motor and perhaps a gearbox. The switching electronics would weigh at most 0.1 kg including wiring. Alternatively, a DC:DC step-down variable transformer, weighing about 0.3 kg, could be used to control the motor [29,30].

Although electric propulsion systems have many advantages over propulsion systems using IC engines [27], the latter have been preferred because of their better system power to mass ratio. This leads to much better endurances than equivalent electric propulsion systems. For example, the 5 kg MERLIN prototypes [30] with their 0.5 kg CCD cameras used 20 Sanyo 1800 SCR nickel-cadmium batteries (NiCads) weighing a total of 1.6 kg, which offered an endurance of only half an hour for a cruising speed of 22 m/s.

The emergence of the samarium-cobalt (Sm-Co) family of hard magnetic materials in the 1970s [31] brought about a revolution in permanent magnetic materials. With their very high magnetic energy densities, Sm-Co permanent magnets were able to bring about reductions in the size and mass of electric motors without a reduction in torque output. Sm-Co magnets offer higher specific power, avoid demagnetisation during switching and offer an efficiency between 66 and 74%. A typical Sm-Co electric motor is the 300 W Astro Cobalt 25 [32], which has a diameter of 40 mm, a length of 63 mm and a mass of 0.34 kg. This motor, which operates at 10,000 r.p.m., cost approximately $ 250 in 1994.

Neodymium-iron-boron (Nd-Fe-B) magnets, a cheaper material than Sm-Co became available in 1983. Nd-Fe-B magnets are presently challenging the more costly Sm-Co permanent magnets in motors to obtain greater torque output in progressively smaller sizes. Furthermore, the older materials including Alnico and ferrites are now being used in more cost-effective ways [33]. Earlier versions of brushless Nd-Fe-B electric motors [34], which yielded a 96% efficiency, were of limited application to a PUMA because the power controller was relatively large and heavy. This problem has been overcome, so that it is now possible to obtain a Nd-Fe-B electric motor of similar dimensions to the Sm-Co motor mentioned above. Although the new electric motors are more efficient, they are limited to applications below 180 °C.

There are basically two types of portable device that are capable of converting the chemical energy of reactants (a fuel and an oxidant) into low voltage DC electricity: the battery and the fuel cell. A battery consists of two dissimilar electrodes immersed in a conducting material such as a liquid electrolyte or a fused salt and when the two electrodes are connected by a wire, a current flows [35]. Batteries come in two distinct types:

- primary such as the zinc-manganese dioxide galvanic cell used in flashlights;
- secondary or rechargeable such as the inexpensive lead-acid (lead-lead oxide) used mainly in the automotive field.

Like batteries, fuel cells generate electrical energy via electrochemical reactions. Unlike conventional batteries, however, fuel cells do not consume materials that are an integral part of its structure or stored within its structure [36]. For example, in a flashlight battery the zinc negative electrode is the fuel while the black positive electrode consisting of manganese dioxide and carbon is the oxidant. A fuel cell consists of a power producing unit (the electrochemical cell) and containers with the stored fuel and oxidant. The reactants are fed to the electrodes only when generation of electric power is required. For most fuel cells, the oxidising agent is atmospheric oxygen. When its other reactant is exhausted, all that is required to resume operation is to replenish the fuel supply.

The theoretical estimates of the energy densities for electrochemical devices should not be taken seriously as they bear little relation to the actual energy density of a device. Furthermore if high discharge rates are involved, then battery energy densities are reduced [27]. Other factors involved in the selection of an appropriate electrochemical device are:

(a) size and mass;

(b) storage and service life (e.g. the shelf life at 20 °C for lithium sulphur dioxide batteries is 5 years);

(c) safety (e.g. lithium-thionyl chloride can explode under very high discharge rates [35]);

(d) starting time - fuel cells based on hydrogen-oxygen alkaline cells require a start-up procedure to minimise the risk of explosion [36];

(e) operating temperature - all electrochemical devices are temperature sensitive with some giving better performance than others for specific temperature regions (e.g. lithium-based batteries have a suggested operational temperature range of - 54 to 60 °C whereas the corresponding range for carbon zinc batteries is between -7 and 54 °C);

(f) cost and availability.

There is no single battery type that has every ideal feature and as a result, a procedure for selecting the most suitable for a specific application must be adopted [35]. The same applies to fuel cells. For the close-range UMA application, the two most critical characteristics of an electrochemical device are its energy and power densities, which are commonly expressed in Whr/kg and W/kg, respectively. In the past when UMA designers have rejected electric propulsion, it has primarily been because of the low energy densities [27] and the short flight endurance offered by electrochemical devices in comparison with their fuel powered counterparts. For example, the Sanyo 1800 SCR NiCads mentioned above have energy densities ranging between 20 and 30 W hr/kg [35], but produce poor endurances [30]. However, the power density of NiCads is high with the recommended maximum power density for the Sanyo 1800 SCR NiCads being about 600 W/kg.

Although lithium reacts violently with water and is difficult to shape and to use safely [37], lithium batteries offer energy densities of up to 330 W hr/kg [35], nearly four times higher than those of alkaline manganese batteries and a factor of 10 higher than NiCads. These primary batteries, which use a non-aqueous organic solvent as an electrolyte, also have high volumetric energy densities, require no special storage provisions and operate between -55 and 180 °C.

Here we concentrate on primary batteries because these currently offer higher energy and power densities than their secondary counterparts. It should be mentioned, however, that both SAFT and W.R. Grace/JCI have been contracted by the US Advanced Battery Consortium to develop rechargeable lithium/iron disulphide and lithium-polymer batteries respectively [38]. The energy and power densities for the former type of battery are projected to lie between 130-200 Whr/kg and 200-500 W/kg while those for the latter type are projected to lie between 100-200 Whr/kg and 100-400 W/kg. The former type is more advanced than the latter, but both types will require significant development before they become commercially viable. It should be noted, however, that Toshiba has already introduced the Portégé T3400 series of subnotebook computers, which are the first portable computers to use rechargeable lithium-ion batteries [39].

There are over 30 different types of primary lithium batteries, four of which are currently used in specialised industrial, medical, scientific and military applications [40]: lithium-thionyl chloride, (which have the highest energy densities), lithium-bromine chloride, lithium-sulphuryl chloride and lithium sulphur dioxide. All four types are capable of high drain rates, i.e. have high power densities. Of these, however, the lithium sulphur dioxide battery has emerged as the most popular [35].

SAFT claims that the electrolytes for its LSH series (lithium-thionyl chloride) virtually eliminate initial voltage delays whilst retaining outstanding storage and low discharge performance [41]. From an examination of the discharge curves at 20 °C, it is estimated that the 120 g LSH20 cell has a power density of about 107 W/kg for a discharge current of 4 A and energy densities of about 350 Whr/kg and 277 Whr/kg for currents of 12 and 60 mA respectively. It can be seen from this that the energy available falls as the discharge rate increases. Therefore, there is an advantage in minimising the required discharge rate by designing for longer endurance. This can be achieved by:

(i) minimising the number of manoeuvres and rapid climbs;

(ii) making the vehicle aerodynamically efficient;

(iii) operating at low speed;

(iv) only making gentle changes to the vehicle's flight path.

For electric powered UMAs the advantages that fuel cells possess over batteries are:

(i) the energy density of a fuel cell is greater than that of a battery. Methanol for use in a fuel cell has an energy density of about 1900 Whr/kg [36] whereas petrol and advanced batteries have energy densities of about 900 and 300 Whr/kg respectively;

(ii) a fuel cell can be reused whereas a primary battery cannot;

(iii) a fuel cell can be reactivated much more quickly than a secondary battery.

The disadvantages of fuel cells include complexity of currently available systems and their volume, weight, cost and lifetime. It is possible to design an Alkaline Fuel Cell (AFC) system using hydrogen fuel that is competitive in weight and volume with an IC engine, except for the storage of hydrogen in the vehicle [36]. The small AFC used in a NASA program had an energy capacity of 2 kW hr and weighed 8 kg [42]. AFCs have uncertain lifetimes and are intolerant to carbon dioxide forming a carbonate in the electrolyte, which is responsible for a loss in performance. Nevertheless, it is anticipated that many of the problems associated with fuel cells will be overcome by further research [36].

Fuel cell power densities are significantly lower than those of conventional batteries. The solution to this problem may be fuel cell-battery hybrids, in which batteries perform most of the work during periods of high power demand such as acceleration and take-off while fuel cells provide the energy during periods of low power demand such as cruising. These hybrids are currently too large for deployment in a PUMA, but a metal-air cell may be suitable.

Metal-air cells, also known as semi-fuel cells or metal-air batteries, are refuellable aluminium-air, zinc-air and cadmium-air cells. The first of these seem to offer the best performance [37,43-45] but are expensive [46], mainly because they are still in the developmental stage. Thus, we should mention that rechargeable zinc-air batteries with energy densities of up to 155 Whr/kg are now available [47]. For example, AER Energy is retailing its PowerPro custom-made rechargeable zinc-air cells for $US 399 to power Toshiba laptop computers. These zinc-air batteries have an energy density of 120 Whr/kg and weigh only 4 lb [48].

Aluminium-air fuel cells consist of an aluminium anode and an air cathode, both immersed in either a saline or an alkaline solution with the latter solution offering much higher energy and power densities. Theoretically, an aluminium anode is able to provide more energy, either by weight or by volume, than any other metal except for lithium. In addition, aluminium consumed in a battery volume for volume releases four times as much energy as burning gasoline and does not produce pollutants. These cells hold great promise for the future due to the relative cheapness of aluminium. As an example of the current state of this technology, Alupower's Low Power Fuel Cell (LPFC) is a backpackable fuel cell which weighs 5.3 kg, has the dimensions of 23(L) X 16(W) X 27(H) cm and operates between -40 and 40 °C [49]. This fuel cell has a very high energy density of 380 W hr/kg, but here is no mention of the recommended maximum power density.

To demonstrate the importance of power densities, consider a 5 kg vehicle with a reasonably good lift to drag ratio of 15, a minimum flight speed of 8 m/s and a 1 kg lithium-thionyl chloride battery made from SAFT LSH20 cells (107 W/kg). The drag on such a vehicle is 3.3 N giving a power requirement of 27 W. Assuming an efficiency of 0.7 for the combined motor and propeller system, 39 W is required from the battery for horizontal flight. Thus a maximum of about 68 W is available for climbing and other manoeuvres, which corresponds to a climb rate of 58 m per minute.

A 1 kg lithium battery, costing about $210, could supply sufficient energy for a 1 hr flight of a PUMA. An endurance of 10 minutes has been achieved with the MERLINs using a 1.6 kg NiCad battery [30]. NiCad energy density is about one tenth that of lithium cells. Later versions of the MERLINs cruised for 5 to 10 hr using lithium thionyl chloride cells [29]. Careful consideration is required in getting the right balance between vehicle performance and endurance and then obtaining the appropriate battery/fuel-cell to match this balance.

It can be seen from the above that there are two practical sources of electrical power for a PUMA: the first is to use aluminium-air fuel cells and the second is to use lithium primary batteries such as lithium sulphur dioxide. In both cases, an electric motor would be required to convert the electric energy into mechanical energy. Lithium batteries are more suitable even though they are not reusable and require some care in their handling. Although both have similar energy densities, fuel cells have considerably lower power densities, which restrict the manoeuvrability and maximum speed of a UAV as well as limiting climb rate.

The total masses of the electrical propulsion systems for a 1 and 2 hr PUMA mission are estimated to be 1.5 and 2.5 kg respectively. The equivalent masses for fuel powered propulsion systems are 1.0 and 1.18 kg. In addition, the batteries are far more expensive than hydrocarbon fuels. Although the mass and energy costs of an electric powered PUMA are higher than a conventionally fuel powered vehicle, the various advantages that the former offer in military operations far outweigh these factors as detailed below.

The advantages offered by electric propulsion systems over fuel powered systems are:

(a) Lower emissions of noise, heat, vibrations, smoke and pollutants. Noise, heat and smoke facilitate the early detection of a UMA by adversaries. Noise emissions may not be crucial when conducting maritime surveillance of the wide open sea, but they are an important consideration for surveillance operations near river banks, coastal inlets and the coves of Australia's northern islands. Vibrations may affect the operation of some systems on the vehicle, particularly the sensor payload. Hence the sensor payload may require additional stabilisation, which, in turn, increases the size and weight of a fuel powered propulsion system significantly and affects the design of the vehicle substantially.

(b) Easier and more flexible control of the vehicle. More care and effort are required in starting an IC engine, increasingly so as the engine ages. Wear and tear affect performance adversely. An electric motor can be started and stopped at will, but an IC engine has to be started pre-flight and usually cannot be allowed to stop until the flight is completed or else the vehicle will be lost. Inflight stoppages may be caused by a fuel interruption brought about by manoeuvres or severe turbulence. The ability to switch an electric motor off enables silent vibration free flight over sensitive areas by gliding for short periods.

(c) Thermal efficiency. The electric motor is considerably more thermally efficient than an IC engine requiring less heat to be dissipated and lowering vehicle thermal emissions. In addition, cooling an IC engine requires a large airflow to be directed over its cylinders, and this may increase vehicle drag.

(d) Less complex installation in the vehicle. An electric motor is simpler to install than an IC engine with its awkward shape, control actuator, cooling system and fuel-feed requirements. An electric motor is cylindrical enabling it to be fitted inside the fuselage of a vehicle without external protrusions such as engine cowlings.

(e) Better reliability, especially in difficult climatic conditions, e.g. tropical Australia, where an IC engine suffers more than an electric motor and IC engine performance is degraded by high temperatures.

(f) Fewer fuel problems. Batteries are easier and safer to store, transport and load into the vehicle than a flammable liquid fuel, which, if spilt or leaks, may damage vehicle structures and sub-systems. Unless the fuel tank for an IC engine is situated at the vehicle's centre of gravity (c.g.), its c.g. will shift as fuel is consumed leading to a change in stability characteristics. Batteries can be placed anywhere in the vehicle and distributed as required for weight and balance purposes. Fuels also deteriorate in tropical conditions leading to power loss or even fuel interruptions during the mission. Some batterries are potential explosion hazards if short circuited but have internal fuses to overcome this problem.

The electric motor is therefore superior in all areas except mass and cost, which are important considerations in the design of a flight vehicle. However, the weight penalty incurred by a small slow vehicle is not prohibitive for flight endurances of about 1-2 hr. The cost of batteries is much greater than liquid fuels, but increased safety and reliability offset this cost. The potential loss of a relatively expensive vehicle and sensor payload should outweigh the possible saving in using liquid fuel and the battery cost is still only a small part of the total system operational cost.

AeroVironment's Pointer is powered by an electric propulsion system consisting of a lithium battery and a 300 W electric motor with a pusher propeller [50]. This UMA can fly for 1.25 hr and has extremely low visual, IR and radar signatures. The electric motor makes Pointer quiet and 'with any sort of noise in the area, you cannot hear the aircraft at 100 feet' [50].

Alupower built a prototype UMA to demonstrate the capabilities of aluminium-air batteries/fuel cells [49]. The propulsion system for this UMA consisted of a geared electric motor, a two-bladed propeller and a 3.7 kg fuel cell. The vehicle, with a mass of around 10 kg, required about 200 W for flight. The prototype batteries were capable of supplying this power for 2 hr giving overall energy and power densities of 120 W hr/kg and 60 W/kg respectively. Note the low power density, which is characteristic of fuel cells.

The Low Observable Electric UAV built by Quiet Air Inc. for Westinghouse used a unique design of an aluminium air cathode fuel cell [23]. This cell has a much higher energy density than regular fuel cells with an output similar to lithium cells. The 7 kg vehicle was able to fly for an hour at 600 m.

Eyrie Enterprises has the capability to build larger versions of the MERLINs, which would weigh about 9 kg and have a 2 kg payload [29]. These vehicles would also have considerably greater range and endurance. Even without resorting to Nd-Fe-B motors, a 15 kg version with 5 kg payload is possible but the future lies more in improving the small UAV than increasing its size since a MERLIN IIS with a fail-safe parachute is unlikely to cause major damage, an important consideration for deploying small UAVs in shipborne operations.

Flight endurances of 1-2 hr can be achieved for relatively simple UMAs by using either small IC engines or electric propulsion systems. The key to performance with an electric UMA is the high efficiency that can be attained through a combination of the propeller, motor, vehicle aerodynamics and structure. This enables a longer endurance to be achieved with the same payload mass on a smaller UMA than with a similar UMA powered by an IC engine [52].

The viability of an electric powered PUMA can best be verified by producing a concept demonstrator and/or by procuring an existing system such as Pointer. Field trials can be used to establish whether these systems are capable of endurances of 1-2 hr and whether these systems are still reliable after many missions. In particular, the effect of a large number of high power manoeuvres, e.g. steep climbs, sharp turns and high speed dashes, needs to be studied in various adverse weather conditions, since these will affect range and endurance, which in turn will affect mission requirements. By producing an electrically powered concept demonstrator with a more aerodynamically efficient design such as a flying wing, it may be possible to extend current endurance and range capabilities of close-range UMAs. Such an exercise could lead to a development of expertise in a new and exciting area of technology, which would would enable evaluation of the strengths and weaknesses of future close-range UMAs in Australian conditions.

## 3.3. Air Vehicles

The air vehicle's purpose is to carry the primary sensor and its supporting systems such as the data link. The size, mass and position of this sensor in the vehicle are very important inputs to vehicle design. In general, sensors should be small/light and positioned to minimise drag. Increases in drag and/or mass lead to greater power requirements needing a larger engine, more fuel and larger air vehicle. The primary sensor is only a fraction of the total airborne system and for every gram of primary sensor there are approximately four grams added to the total mass. Range is limited by the vehicle's fuel carrying capability, its aerodynamic drag and flight speed. Power requirements and fuel usage both increase rapidly with speed. Many trade-offs can be made to optimise the power, endurance and range for various vehicle configurations [53].

### 3.3.1 Fixed Wing Unmanned Aircraft

The choice of vehicle configuration is dependent upon many factors including aerodynamic efficiency, robustness, payload needs and other requirements such as low radar cross-section. For surveillance and reconnaissance missions the primary sensor should be forward-looking and located in the nose of the vehicle to achieve minimum drag. A steerable sensor capable of looking to either side and downward as well as forward is the best option. As a result, the propeller may need to be located elsewhere and should be a pusher configuration behind the wing and fuselage. This enables the propeller slipstream to be kept clear of the vehicle's surfaces, although on occasions having the control surfaces and/or lift surfaces in the slipstream extends the flight envelope usefully, e.g. in the recovery of the vehicle.

To achieve low mass the vehicle should be formed from epoxy composites incorporating kevlar, carbon or glass fibres. These materials have a high strength to mass ratio, minimal fatigue problems and are poor reflectors of radar signals. For ease of handling and recovery it is desirable to use a high wing vehicle with a pusher propeller [21]. However, a simpler and more robust configuration is the flying wing vehicle. A flying wing airframe with a wing-span of 3.6 m and aspect ratio of 12 would weigh about 3 kg, if constructed from epoxy composites. The high aspect ratio is desirable to minimise induced drag. Since the PUMA is to be battery-powered with a fixed vehicle configuration and is to carry the same payload on all missions, no shift in the vehicle's c.g. is likely to occur in flight or between flights. For simplicity, flaps or other devices producing large pitching moment changes should be avoided. With a fixed c.g. and no large changes in pitching moment a slightly-swept flying-wing such as the Aquila [16,54,55] becomes viable.

Flying wings approach the best conventional design in any measure of aerodynamic efficiency and are unmatched structurally as carriers of the solid, dense battery-packs comprising up to half the total mass [29,30]. According to Eyrie Enterprises, which developed the 'Merlin' UMAs (see Fig. 8 for the vehicle configuration), problems that in the past have led to the many failures in deploying flying wing vehicles can be overcome by incorporating a sophisticated autopilot. Merlins are true flying wings compromised minimally to accommodate sensors and have fins for greater yaw stability. In particular, the Merlin II has a wing-span of 2.6 m, or 2.8 m with tip sails canted at 30°. The wings are swept back 18.5° with an area of 0.77 sq m while the total mass is 5 kg which includes a 35 mm still camera.

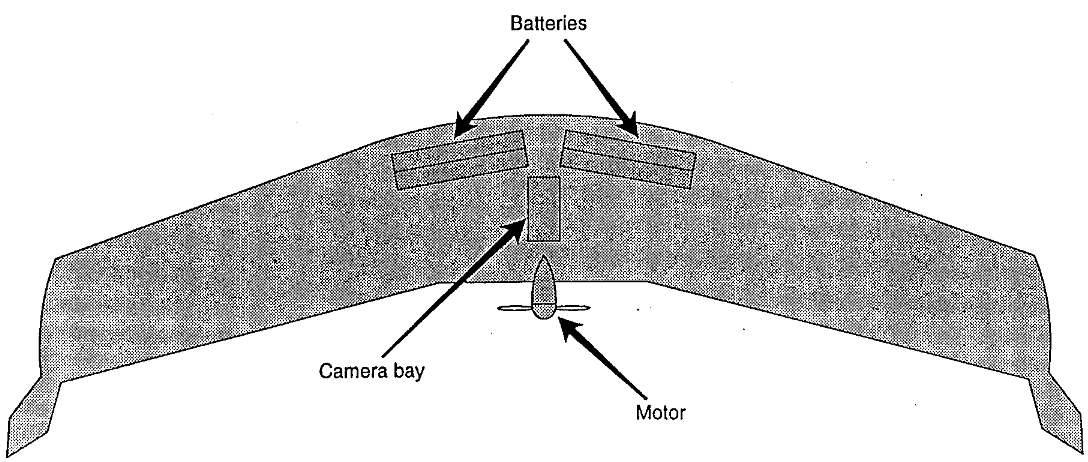


*Figure 8: Eyrie Enterprises Merlin II*

The problems with a flying wing are:

(1) its handling at launch time;

(2) its stability and control during flight;

(3) the protection of its propeller on landing.

The propeller needs to be on or near the longitudinal axis of symmetry to avoid changes in pitching moment due to fluctuations in power and this means that the propeller will hit the ground when the vehicle lands. To provide some protection for the propeller and for the personnel handling the PUMA when the motor is running, a duct may be placed around the propeller as in Aquila. Although a duct contributes both to drag and the mass of the vehicle, it increases propulsion efficiency and thus may improve overall performance.

Another configuration that does not have the problems associated with flying wing vehicles, but is aerodynamically less efficient, is a high wing with a tail plane and a pusher propeller above the fuselage as in AeroVironment's Pointer. Pointer borrows heavily from radio-controlled model aircraft techniques, can be hand-launched and is essentially an electric powered sailplane with a fixed visible-spectrum TV camera in the nose [56,57]. The air vehicle is stored in six sections [50,51] and assembled by push-fitting the sections together. The airframe is made of a kevlar composite together with some fibre glass and styrofoam and is 1.9 m long with a wing-span of 2.7. It has an aspect ratio of about 10 and a total mass between 4 and 5 kg [50,51,57]. Its maximum speed is 80 km/hr while its cruising speed is 35 km/hr. The maximum rate of climb is 3.1 m/s and the operating height range is 50-300 m. The patrol radius is 8 km.

## 3.4. Launch and Recovery

Launch and recovery, in particular, are critical phases in UMA operations. Fortunately, the smaller the recovered vehicle, the easier the problems are because of the lower amount of kinetic energy that needs to be dissipated and the larger strength to mass ratio of the vehicle.

Small UMA launch and recovery methods depend on numerous factors including:

(a) the UMA's size and mass;

(b) the size and cost of the launcher;

(c) the amount of open space available;

(d) the type of launching base, i.e. off a ship or from land;

(e) timeliness and disposability.

The last issue pertains to the time involved in both launching and recovering the vehicle in addition to the time and effort involved in deploying the entire system, so as not to preclude other activities from being accomplished by personnel. With regard to this issue, it should be noted that current NATO requirements for naval operations allow a maximum of ten minutes to clear a ship's deck of UMA launch and recovery equipment [58].

The most common launch methods, some of which are illustrated in Fig. 9, employ:

(i) hand-launching, where the UMA is thrown like a javelin;

(ii) catapult launchers;

(iii) takeoff and landing on a runway.

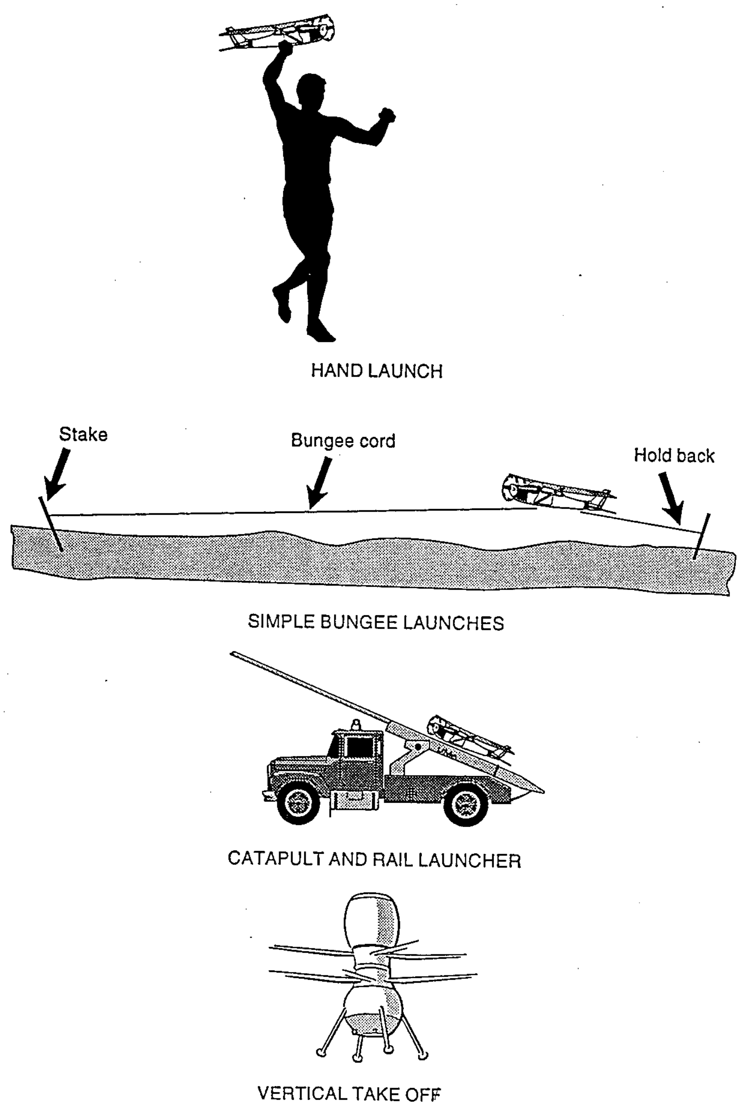


*Figure 9: Launch Methods*

### 3.4.1 Launch Methods

The larger catapult launchers consist of a long rail where the UMA is launched either pneumatically, hydraulically, by means of an engine or by a spring while the simplest catapult launchers are bungee launchers where an elastic rubber (bungee) is staked to the ground to create a slingshot for launching the vehicle.

Large catapult launchers are very unpopular for both land- and ship-based operations. The alternatives are hand-launching or using a bungee. The major problem in launching UMAs by hand is that there is a limit to the mass which can be physically launched. For example, if the total mass of a UAV such as Pointer were to increase by only a few kg, then it would not only be very difficult to launch by hand but it could also cause injury to the operator.

A bungee launcher is suitable for vehicles with masses up to 30 kg and take-off speeds less than 18 m/s [21]. In land-based applications care must be taken to ensure that the bungee is securely staked to pegs and that no one is in the direct path when launching the UMA. Bungee launchers may lose their effectiveness in icy conditions, although this should not be a problem in ADF applications.

A different approach is needed for launching a light UMA such as Pointer from a ship due to the limitation in space. A shipborne launcher should compensate for the ship motion so that the UMA can be launched at the correct attitude and airspeed. This requires a steerable launcher, e.g. a bungee folded around a special guiding rail, conveniently clamped to the ship's rail and manually steerable. In addition, for safety reasons, the vehicle should not be launched directly into strong wind.

### 3.4.2 Recovery Methods

Methods for recovering UMAs [21] include:

(a) landing on wheels at a prepared landing site with the optional use of wheel brakes, reverse thrust, drag chutes (parasails) or arrestor wires to reduce landing distances;

(b) skid landing on comparatively smooth terrain;

(c) releasing a parachute;

(d) guiding the vehicle into a net [59].

There is also another interesting possibility for ship-based operations utilising an arrestor hook, which is described below. Finally, another option is to land light and slowly-moving vehicles without any special aid.

#### 3.4.2.1 Shipboard Recovery

Shipboard recovery is a serious problem, especially for naval operations involving large UMAs. UMAs need to be recovered without causing damage to the operators, the UMA or the ship. The kinetic energy of a large UMA travelling at flying speed must be dissipated while landing it accurately in a confined space. Small UMAs such as Pointer are much easier to stop, do not pose a significant risk to a ship and do not require sophisticated recovery equipment. In addition, Pointer is sufficiently inexpensive to be considered as semi-expendable and is made up of a number of easily replaceable parts, e.g. after a hard belly-landing, only the damaged portion (if any) of its fuselage pod need be replaced.

Two of the methods for shipboard UMA recovery use nets or an arrestor system. A net requires no additional flying hardware and the vehicle can be flown directly into the net suspended above or along side the ship. The advantages in using a net [60] are that:

(a) it forms a protective barrier;

(b) it can provide a large capture area;

(c) the UMA is not required to carry special recovery equipment.

Disadvantages are:

(i) retardation in limiting design conditions may cause damage to the UMA (including unshrouded propellers) and the net;

(ii) nets need to be large to allow for ship motion and flight path divergence due to turbulence;

(iii) nets may be somewhat difficult to deploy over the side of a ship because of the need for a supporting frame;

(iv) there is a possibility that the UMA will miss the capture area of the net, with the potential thereby to damage itself and/or the ship.

#### 3.4.2.2 Shipboard Arrestor System

In an arrestor method of recovery [60] a hook and 'wire' system is used. At recovery time the UMA deploys a parasail, whose function is to lift and spread the 'wire' consisting of synthetic risers and cross members. The UMA is guided so that the wires engage with a hook at the end of a swinging boom extended from the side of the ship.

The advantages claimed for this method are :

(a) the retardation force is applied aft of the c.g. enabling the UMA to remain stable and to follow a predictable path;

(b) retardation loads are absorbed by specially designed load paths which mean that high retardation rates can be used;

(c) the method of propulsion for the UMA and its position are not critical;

(d) the capture device can be placed at the ship's side, (i.e. on the up wind side) away from the worst turbulence;

(e) if the UMA misses the hook it has a safe overshoot path.

Disadvantages are that:

(i) the system does not act as a barrier;

(ii) the UMA needs special recovery equipment;

(iii) the capture window may be smaller than is reasonably achievable with a net.

Whilst the above recovery method is applicable to most UMAs, a simpler approach not requiring a parasail could be used for the PUMA. The PUMA could deploy a cable with a hook and/or a paravane at its rear to engage a comb-like boom extended from the side of a ship. An energy dissipation mechanism would be included in either the boom, the trailing cable or the UMA to brake the vehicle's movement. The capture window for this recovery method is approximately equal to the area covered by the length of the boom and the height of the trailing cable. If the UMA fails to engage the boom, then it has a clear overshoot path as depicted in Fig. 10.

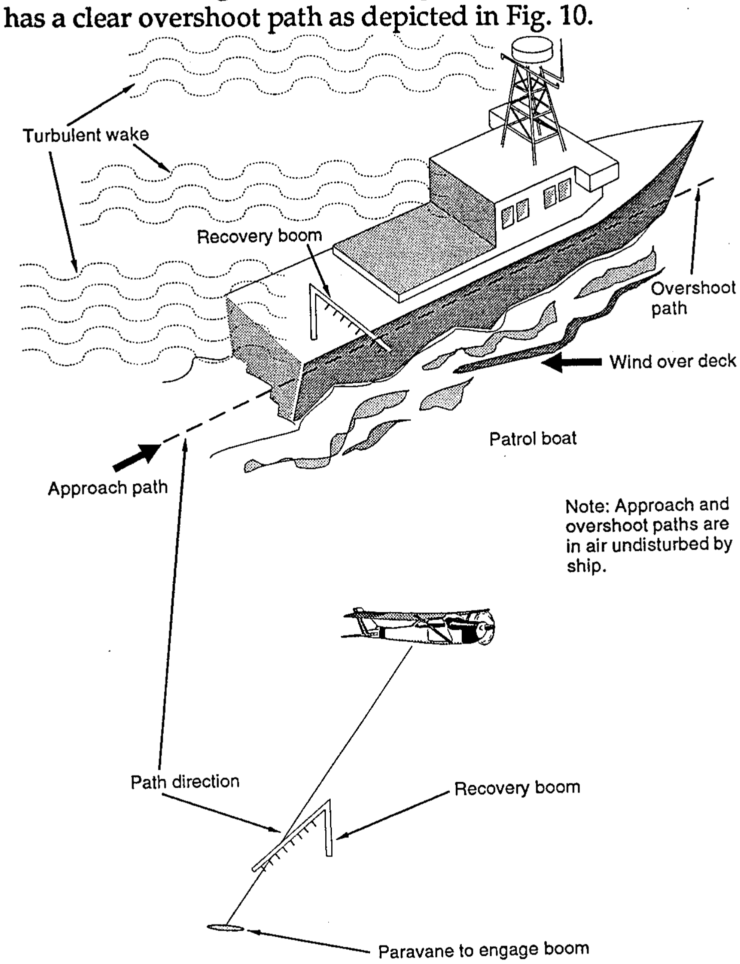


*Figure 10: Method of Recovery*

## 3.5. Navigation and Control

Navigation is defined here as the art or science of determining the position, orientation and velocity of an aircraft at any time [61]. The last two may be optional in some systems. The term guidance is concerned with the determination and generation of steering or correction command signals to enable an air vehicle to be moved from one position to another. Basically, a control system performs two functions:

(a) it receives correction command signals and adjusts the flight direction accordingly;

(b) it maintains stability [62].

Some sensors can be shared by both the navigation system and the control system to avoid unnecessary duplication. Alternatively, the navigation and control systems can be integrated into one unit performing both functions.

### 3.5.1 Control

The degree of remote control and guidance for UAVs can range from direct radio control of the flying surfaces to that of a completely autonomous vehicle which can be preprogrammed to conduct a mission without requiring further guidance. The first extreme is of limited value since it requires a high degree of operator skill and attention and is limited to the visual range and direct line of sight. The other extreme is difficult to achieve and very expensive due to the complexity, high grade sensors required and space/mass limitations. Most UMAs have control systems lying between these extremes with the actual level of control and guidance being determined by mission requirements. For example, a sophisticated and hence highly accurate navigation and control system is required to conduct target designation whereas to achieve the 'What's over the next hill?' requirement, as in the case of Pointer, only a simple and cheap control system is required.

A control system may perform the following functions [63]:

(a) stabilise the vehicle in pitch, roll and yaw;

(b) hold attitude;

(c) implement demanded changes in attitude;

(d) hold heading;

(e) acquire demanded heading;

(f) hold height;

(g) acquire demanded height;

(h) control throttle or speed.

One of the disadvantages of the flying wing configuration outlined in Sec. 3.1.2 is that it has only a marginal natural stability and consequently, control can be difficult. Flying wings are also very sensitive to residual pitching moments arising from certain manoeuvres. Therefore, a flying wing UMA would require a sophisticated autopilot to maintain adequate control.

To provide guidance and maintain stability a control system needs to consist of:

(i) a sensor unit;

(ii) a data link;

(iii) a controlling computer;

(iv) software;

(v) actuators or servos.

The CPU would be combined with the sensor unit and actuators to form an autopilot, which is basically a closed loop system providing feedback into the actuators to control vehicle motion.

With a flying wing two actuators are required to manipulate elevons (a combination of elevator and aileron) attached to the rear of the vehicle's wings. The elevons can then be raised and lowered, both synchronously and differentially. Although not necessary but nevertheless practical, a third actuator could be utilised to manipulate a fin or rudder on the vehicle, thereby maintaining yaw stability. Yaw control for a flying wing can also be achieved by differential power to twin motors [29]. Hence fins, which are often a vulnerable part of an aircraft, are not required. Alternatively, Pointer which resembles a model airplane with a sharp dihedral, pylon-mounted wing and is thus inherently stable does not require ailerons [64]. However, a rudder is required to control direction or heading while an elevator or stabiliser is used to vary the attitude.

### 3.5.2 Navigation

Navigation becomes progressively more difficult as the UMA's range and endurance are increased and as its size and cost are reduced. UMAs can be navigated by a variety of methods ranging from direct remote control for line of sight (LOS) operations to completely pre-programmed flight for over-the-horizon missions [65]. Apart from direct observation of a UMA over very short distances, there are basically two classes of navigation systems that can be utilised by UMAs [66]:

(a) dead reckoning systems;

(b) position fixing systems.

Dead reckoning is the determination of position by measuring the direction of motion and distance travelled. Position fixing is the determination of position without reference to any former position. Navigation systems may be one or the other or a combination of both types such as a doppler/inertial navigation system [67].

#### 3.5.2.1 Dead Reckoning Navigation

Basic dead reckoning methods using airspeed and direction are not likely to be sufficiently accurate while inertial navigation systems are too heavy and expensive for the deployment in the PUMA. The major components of a sensor unit for the PUMA's control system are:

(a) two or three solid state rate gyroscopes;

(b) a pressure transducer or altimeter;

(c) magnetometer to determine heading;

(d) an airspeed sensor;

(e) accelerometers to establish a vertical reference.

An attitude gyro could be use as an alternative to accelerometers and rate gyros on the pitch and roll axes.

The above combination forms an Attitude and Heading Reference System (AHRS) [67]. These systems are typically used when a vehicle is required to travel in a specific direction over a given period. For example, the MACHAN UMA strapdown AHRS is made up of miniature GI-G6 single degree of freedom rate gyros, AP-G6 accelerometers and a TI9900 microprocessor [68]. This system is rugged and reliable, lends itself to modular design and has a system activation time of 5 s. An AHRS used primarily for control may provide a limited short term navigation capability with a position fixing system providing long term corrections.

#### 3.5.2.2 Position Fixing Navigation

The most promising position fixing navigation system is the NAVSTAR Global Positioning System (GPS). GPS is based on a constellation of 24 US satellites which provide information on a continuous basis that allows anyone, on or near the surface of the globe, equipped with a suitable receiver to get a position fix. The accuracy of the fix depends on whether a commercial unit or a military unit equipped with a 'p' code capability is used. The commercial versions are accurate to within 100 m while the military units are accurate to within about 15 m. The latter are also more jam resistant. Miniature GPS receivers are currently available, e.g. the Virginia Slims hand-held unit

which weighs 0.23 kg and has a volume of 100 cc [69]. Motorola's Government and Systems Technology group in Arizona is also marketing a search and rescue handheld transceiver called the GPS-112 [70]. Furthermore, the same reference adds that with micro-machined technology future GPS receivers will appear as page-sized units or even wtach-sized packages. Such a system would be suitable for deployment in the PUMA, but might require a DC:DC converter.

Many existing UMAs use their data link to obtain a position relative to the GCS. These systems are claimed to be accurate to within 50 m, but this is dependent on the tracking accuracy of the GCS antenna which may not be achievable using the simple GCS proposed for the PUMA system. In addition, when passing information to units outside the UMA system, a common reference system such as GPS is of great benefit. The ADF favours GPS as a common reference and many UMA systems either offer GPS capability already or are planning to do so in the near future. Therefore, GPS is currently the best option for navigating a PUMA system.

It should be mentioned here that Lynxvale of Cambridge is marketing a simple low-cost navigation called Cursor that uses local radio and television frequencies to pin-point a vehicle [71-73]. This system does not require the installation of costly transmitter networks either on the ground or on satellites and is claimed to be more accurate than GPS systems, especially in built-up areas or during atmospheric disturbances. Although the size of a car radio, it is perhaps too large and too heavy for deployment in the PUMA at the moment, but further development of this system should be investigated for it removes the need to rely on another country's satellite system, which is more in line with the Australian Government's broader conception of self-reliance in defence as discussed on p. 13 of The White Paper [1]. Furthermore, according to Hewish [74], GPS is not a panacea and defence forces are increasingly specifying hybrid systems that contain the best of all possible worlds. To emphasise this point more, within a month of being declared ready for civil use in early 1994, three satellites of the constellation were found to be unusable and another two were out of service for periods ranging from 10 min to 24 hr [75].

# 4. Data Link

Control of the PUMA and transmission of real time data to the GCS are carried out via data links. A narrow band uplink is required for the control of the vehicle, while a narrow band downlink and a wide band downlink are required respectively for monitoring the vehicle and for the transmission of primary sensor data. Both downlinks can be combined. Transmission of real time TV pictures at 25 frames per second or greater without any data compression requires a bandwidth of at least 5 MHz. Such wide bandwidth transmission can only occur in either the very high frequency (VHF) or ultra high frequency (UHF) bands and is limited in range to LOS. In addition to the LOS limitation, the range is limited by signal strength considerations and antenna gains. Normally the flight vehicle has limited power available and operates with an omni-directional antenna. However, the GCS can have a high gain

directional antenna capable of high transmission power, thereby maximising the range. Typical UMA data link ranges with this configuration lie between 40 and 50 km. For the PUMA with its limited amount of available power from the GCS and less accurate directional antenna, the latter implying that a larger beam width is required to track the vehicle, a lower maximum range ensues since in most operations maximum UMA range is determined by the maximum range at which it can be controlled.

Reducing the frame rate and/or compressing transmitted data are methods of reducing the size of a bandwidth. A smaller bandwidth allows for the following possibilities:

(a) Transmission at the original frequency and power leads to better Signal to Noise Ratios, or in the case of digital data reduced Bit Error Rates (BER). This improvement can be used to extend the range or provide better immunity to external interference;

(b) The transmission power may be reduced by trading the improved SNR/BER against transmission power;

(c) The improved SNR/BER can be traded for a wider antenna beam width (thereby reducing directional antenna requirements) or a longer range;

(d) For cases where a very large reduction in the bandwidth can be achieved, the LOS restriction may be overcome by operating the transmission data link in the high frequency (HF) band.

There are several data compression techniques based on transform coding that may be employed for UMA data links as described in Ref. [76]. Currently, the most widely used of these is the Discrete Cosine Transform (DCT). Hardware implementing the Joint Photographic Experts Group (JPEG) algorithm for this technique [77-80] is commercially available and offers a compression ratio of about 20:1 without significant degradation in the received image. In fact, Wilson [77] states that in many situations it is possible to compress an image by as much as 24:1 without visible deterioration and by 96:1 still maintaining an acceptable image. In more recent work, Walmsley et al have succeeded through the use of pruning to increase the speed of implementation of the algorithm [81].

Data compression techniques based on non-conventional transform coding which incorporate either fractal [82-84] or wavelet [85] theory (or even both [86]) are still under development. Both techniques offer very high compression ratios. In comparing wavelet transform coding with the DCT (JPEG) method Cohen and Resnikoff [87] have concluded that wavelet transform coding provides better quality and higher compression ratios for most source imagery. In particular, they show that the quality of the 16:1 wavelet compressed 'Lena' benchmark image is much superior to the corresponding DCT image. Fisher [88] has demonstrated that fractal encoding employing HV-rectangular partitioning [89] outperforms some wavelet schemes, DCT (JPEG) and other fractal techniques at moderate to high compression ratios by

applying the epic wavelet, DCT (JPEG) and HV fractal techniques to a 512×512 8-bit image. Although the HV fractal technique is marginally better than the epic wavelet technique at a compression ratio of 58:1, Fisher shows that both techniques are much superior to the DCT (JPEG) scheme, which gives a significantly degraded (but still recognisable) image for a compression ratio of 54:1.

Originally, fractal transform coding offered many desirable features such as high compression ratios, good image quality and resolution independence of the decoded image, but suffered from the long time taken to encode images. Thus, it was unable to provide a near real-time capability as required for a PUMA data link. A major breakthrough towards solving this problem was accomplished by Jacquin [90], who was first to develop a fast algorithm to carry out the search for fractal objects in the domain block. Since then many search algorithms have been devised, which are described in Refs. [91] and [92]. Even faster techniques have been presented recently in Refs. [93] and [94]. Therefore, coupled with the ever-increasing advances in microprocessor chip technology there is more than a possibility that real time fractal encoding/decoding of images/video will be achieved in the not too distant future.

The data link for the PUMA, in the short term, could be based on DCT compression operating in the VHF/UHF bands and have a LOS range of about 30 km using a directional antenna. Assuming that images could be compressed sufficiently quickly, a longer term aim could be to use either fractal or wavelet data compression techniques, combined with reduced frame rates either:

(a) to extend range;

(b) to improve jam resistance;

(c) to remove LOS limitations (by operating in the HF band);

(d) to reduce directional antenna requirements;

(e) or a combination of the above.

# 5. Discussion

This report has presented a review of UMA technologies relevant to a PUMA. The limitations and capabilities of a number of current UMA systems have been examined, including the various subsystem technologies comprising UMAs. We have paid special attention to the developments in sensor payloads, launch and recovery methods, data compression techniques, air vehicle designs and to propulsion, navigational and control systems. Special attention has been devoted to electric propulsion and data handling.

Sec. 2 identified ADF missions/operations that could be enhanced by the introduction of a close range UMA, although such a vehicle may not be the only means for improving these missions. Specifically, a close range UMA could be used by land based patrols and by RFSUs in monitoring activities close to river banks. Their deployment by naval patrol boats to conduct reconnaissance and surveillance operations in either an open sea or near coastlines would be limited by the short endurance and weather conditions, namely wind strength. However, an operating radius of up to 30 km should be achievable, especially if tactics to circumvent wind effects are employed. The endurance could be extended by deploying another system as the first one nears the end of its mission.

In this report we have examined the feasibility of a close range PUMA whose broad requirements are:

(a) a system that possesses both a portable air vehicle and GCS;

(b) an air vehicle with extremely small radar, noise, heat and vibration signatures;

(c) a low mass sensor payload possessing a night time capability.

AeroVironment's Pointer is a currently available PUMA, but this system has serious limitations that make it unsuitable for the ADF missions described in Sec. 2. The most serious limitations of this UMA are its inability to operate at night and its operational range of only 5 km. Furthermore, UAV planners found that Pointer was too small and slow [95]. Although Marine Corps units reported some success with the system in the Gulf War, it needs to be equipped with a satellite-based navigation system to cope with the featureless terrain of a desert or other featureless areas. (At present Pointer does not have a navigation system but relies instead on remaining in sight of the operator and/or using the returned pictures for position fixing.)

This study proposes a Portable UMA (PUMA), as depicted in Fig. 11, which incorporates the latest technological advances in UMA subsystems. The proposed PUMA vehicle is a flying wing with a ducted fan and slightly swept wings. Such a vehicle would possess minimal radar signature, thereby delaying the detection and identification of the vehicle by an adversary. The vehicle should have an aspect ratio of about 12 with a wing-span of approximately 3.6 m. To minimise mass whilst at the same time maintaining structural strength, the airframe should be constructed from an composite such as epoxy kevlar and weigh less than 3 kg.

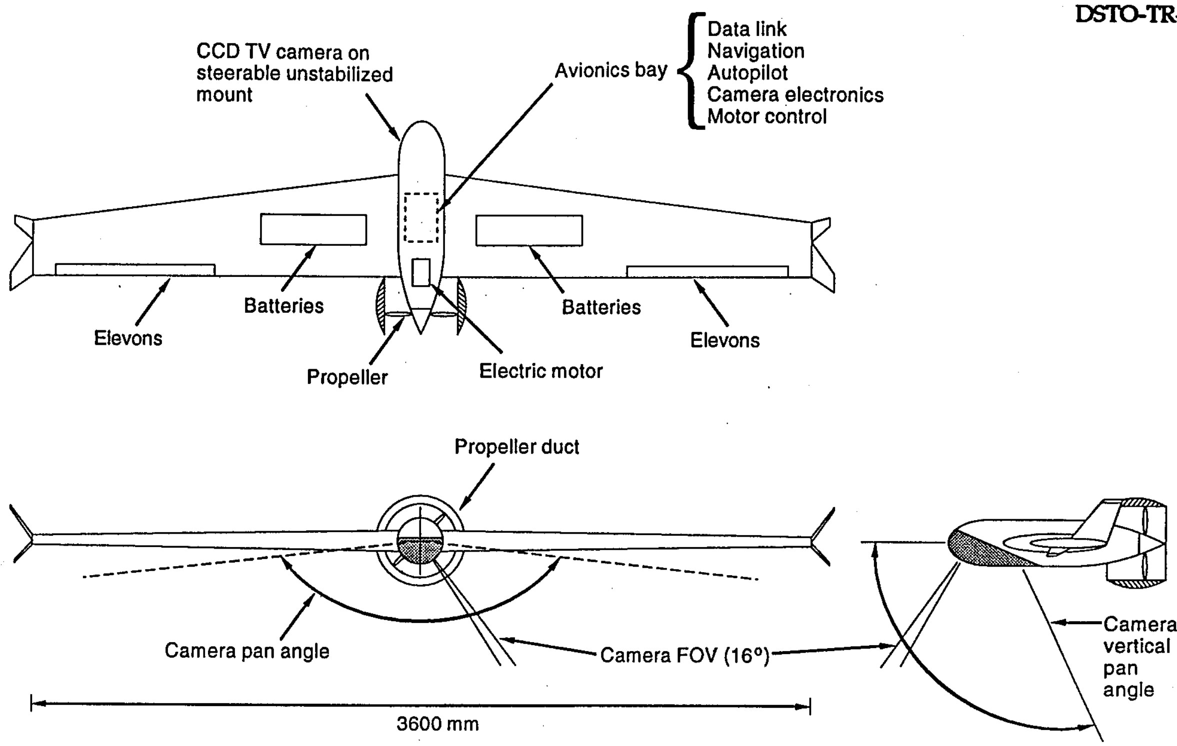


*Figure 11: Portable Unmanned Aircraft Layout*

To minimise acoustic, heat and vibration signatures, the air vehicle should be powered by a rare earth electric motor weighing about 0.5 kg with approximately 3 kg of primary lithium batteries or metal air fuel cells. Detection of the vehicle becomes increasingly difficult as acoustic and heat signatures are reduced whilst minimising vibration facilitates the operation of the sensor payload. Other advantages that electric powered vehicles have over their IC counterparts are safety, ease of launch and a power on/off capability. The disadvantages are additional mass, which is not so significant for small vehicles such as a PUMA and the cost of the batteries or fuel cells. The PUMA is expected to possess flight speeds ranging from 20 to 70 kn. However, because a flying wing is not as easy to control as the dihedral sailplane design of Pointer, the PUMA would require a more sophisticated autopilot to conduct its missions.

A maximum payload of 3 kg is desirable which would enable the vehicle to carry a steerable, but not stabilised, CCD camera fitted with an image intensifier. This would provide a daylight video capability (CCD camera alone) with a limited night vision capability in light levels down to clear starlight conditions. The ability to steer the sensor (for scanning an area or tracking a target) is highly desirable. This may be possible within the payload mass, but no sensor stabilisation should be implemented (larger UMAs have steerable and stabilised sensor mounts). Image stabilisation may be unnecessary provided vibration levels are minimised by using electric propulsion and turning the motor off for short periods. In addition some form of image stabilisation may be possible using image processing techniques in the GCS.

The total mass of a PUMA with the above features is expected to be in the vicinity of 10 to 12 kg and would, therefore, be considerably heavier than Pointer, whose total mass is less than 5 kg. The proposed launch method is to use either a rubber bungee or if possible, some form of catapult that can be easily assembled and disassembled. For land based operations, the PUMA could be recovered by flying the vehicle into a net or by executing a belly-landing. In the case of naval operations, the two possible recovery aids are a net or an arrestor system. A net requires no additional flying hardware while the arrestor system requires the UMA to carry some additional equipment, but is likely to provide safer and more reliable recovery (see Sec. 3.2 for details).

Pointer's restricted range appears to be due to the lack of a suitable navigation system and/or the low gain of the manually pointed data link antenna. Sec. 3.5 indicates that low cost (about $5 K) and compact GPS receivers are currently available. Such a system would enable the PUMA to be navigated over long ranges and facilitate the use of a high gain tracking antenna at the GCS to increase the data link range.

Sensors used for stability and control would form an AHRS consisting of at least two solid state rate gyros, a pressure altitude transducer or altimeter, either a compass or a 3-axis magnetometer to determine heading and an airspeed indicator. In addition to enabling the GCS operator to control the vehicle's flight, a combined navigational and control system would be capable of providing accurate navigation data beyond visual range.

The GCS would be similar in form to a laptop computer with software to display sensor data and flight control data in a windows type environment. This would allow primary sensor data to be presented in one window, vehicle parameters in another, mission, planning data in another and vehicle control to be operated from another window. The windows can be selectively resized by the operator depending on the flight aspect being used (e.g. pre-flight planning uses mission planning window). With a high level of automation in the control system the operator may then operate the vehicle by controlling the primary sensor with the control/navigation system manoeuvring the vehicle to accommodate the sensor demands.

In addition to military applications, there are numerous civilian applications where a PUMA could be of great benefit. For example, the ability to elevate a sensor through the deployment of a PUMA would provide much greater coverage in monitoring fire activity than ground-based observation. It would be much more cost-effective than deploying manned aircraft and by not requiring an airfield, it would also be more flexible. Other civilian applications include maintaining the security of large properties, monitoring shark activity, surveying pipelines and power lines, and search and rescue. It should be noted, however, that many of these applications may require a longer endurance than that provided by the PUMA discussed in this report, but since the PUMA is expected to be relatively inexpensive, this problem could be remedied by deploying a second PUMA as the first nears the end of its first mission and then recharging the latter's batteries for another mission. In some of these operations noise and heat emissions do not pose a problem and hence the requirement for an electrically powered vehicle over a conventionally powered one may not be as

important as in the military operations described in Sec. 2. An IC engine would have the extra advantages of extending the endurance and reducing fuel costs for these applications.

# 6. Conclusion

A Portable UnManned Aircraft system (PUMA) can enhance certain ADF surveillance capabilities. The cost of acquisition and operation of a PUMA would be much lower than that of larger more capable systems. The perceived limitations are a range of less than 30 km and limited night vision, although full night vision may be possible in the future. Advantages of the system include a low acquisition cost and operation by one or two personnel. It could be transported by a vehicle such as a Landrover but would only be part of the vehicle's load, thereby providing an enhanced capability to small units such as the Regional Force Surveillance Units. Larger more capable UMAs require dedicated vehicles, full-time support personnel and a large area (possibly even a sealed runway) from which to operate. This limits flexibility and makes them unsuitable for small mobile units, hence catering only for operations at the battalion or brigade level. Even if a larger UMA system were acquired, the PUMA would still be required to provide timely information to patrol units providing a short reaction time with minimum infrastructure and manpower costs.

The PUMA could also provide low cost experience to personnel before moving to a more sophisticated larger system. It would provide 50 to 60% of the capability of much larger systems (based on day plus partial night capability) for a few per cent of the total cost of acquisition and operation of the latter. Furthermore, production of the entire PUMA system falls well within the capabilities of Australian industry and would enable Australia to enter UMA development and production.

# 7. References


1. Ray, R. (1994) *Defending Australia*, Aust. Gov. Publ. Service, Canberra, Ch. 4.

2. Beazley, K.C. (1987) *The Defence of Australia*, Aust. Gov. Publ. Service, Canberra.

3. Moore, R.A. (1989) *Aerospace America*/Feb. 1989, pp. 26-38.

4. Sweetman, B. (1988), *Interavia 8*/1988, pp. 775-780.

5. Gwynne, P. (1987) *High Technology*/Jan. 1987, pp. 38-43.

6. Sweetman, B. (1985), *International Defense Review 11*/1985, pp. 1771-1785.

7. Berenson, P.J. (1988) *RPVs Remotely Piloted Vehicles*, Seventh International Conference, Bristol UK, Sept. 12-14, 1988, Supplementary Papers, p. K.1.

8. Miller, J.B. (1988) *M.S. Thesis*, Naval Postgraduate School, Ca., USA.

9. Franklin, R.M. (1988) *RPVs Remotely Piloted Vehicles*, Seventh International Conference, Bristol UK, Sept. 12-14, 1988, p. 3.1.

10. Defence Operational Concepts and Capabilities Committee, Headquarters Australian Defence Force (HQADF) (1989) *Opconcepts 4*, Canberra (Confidential).

11. Defence Operational Concepts and Capabilities Committee, HQADF (1989) Draft of *Operational Concept for Army Aviation in Land Operations*, Canberra (Confidential).

12. HQADF (1990) *Exercise Kangaroo 89 Post Exercise Report* Executive Summary, Canberra, (Confidential).

13. Dibb, P. (1986) *Review of Australia's Defence Capabilities*, Aust. Gov. Publ. Service, Canberra.

14. Military Strategy and Concepts Branch, HQADF (1990) Draft of Operational Concepts for Maritime Operations in the Defence of Australia (*Opconcepts* 3), Canberra, (Confidential AUSTEO).

15. HQADF (1989) *Exercise K 89 Post-Exercise Report* Maritime Operations, Canberra, p. 8 (Confidential).

16. Anon. (1986) Technical Survey: *Remotely Piloted Vehicles*, Aviation Week & Space Technology, April 28, 1986. See p. 127 in particular.

17. Jack, J.W. and Houston, A. (1989) AGARD Conference Proceedings No. 436 *Guidance and Control of Unmanned Air Vehicles*, AGARD-CP-436, p. 43.1.

18. Hewish, M. (1994) *International Defense Review 8*/1994, pp. 43-48.

19. Fairchild Weston Systems Inc. (1988) *CCD Technology* (brochure).

20. Gourley, S. and Hewish, M. (1995) *International Defense Review 5*/1995, p. 5.

21. Davey, R.F. (1989) Divisional Note CSF/G12, Combat Systems Division, WSRL, DSTO Salisbury, S.A., Australia (Restricted).

22. Biddulph, C.J. (1987) *RPVs Remotely Piloted Vehicles*, Seventh International Conference Bristol UK, 12-14 Sept., 1987, p. 16.1.

23. Anon. (1988) *Military Robotics* 2, Nov. 30, 1988, p. 24.

24. Anon. (1989) *Military Robotics* 3, July 26, 1989, p. 14.

25. Hooton, E.R. and Munson, K. (Eds.) (1990) *Jane's Battlefield Surveillance 1989-1990*, Jane's Information Group, Surrey, p. 199.

26. Catchpole, B.G. (1975) *Propulsion Systems for Australian Remotely Piloted Vehicles*, Mechanical Engineering Technical Memorandum 366, Aeronautical Research Lab., DSTO Melbourne.

27. Wittenberg, H. (1977) *Engines for Small Propeller-Driven RPVs'*, AGARD Advisory Report No. 101.

28. Taylor, C.F. (1960) *The Internal Combustion Engine in Theory and Practice*, Vol. 1, M.I.T. Press, Boston, p. 409.

29. Falconer, N. (1987) IEE Colloquium on *Unmanned Aircraft Avionic Systems* (Digest No. 103), pp. III4/1-4.

30. Falconer, N. (1987) *RPVs Remotely Piloted Vehicles*, Sixth International Conference, Bristol UK, 6-8 April, 1987, p. 9.1.

31. Cook, J.S., Day, R.K. and Dunlop, J.B. (1987) *Materials Australasia*, May 1987, pp. 20-21.

32. Pine, P. (1987) *The Australian Electric Flight Handbook*, Moore Park Model Supplies, Armidale, NSW.

33. Bartos, F.J. (1988) *Control Engineering*/Dec. 1988, pp. 45-6.

34. O'Neill, G. (1991) CSIRO's *Magnetic Motor Points to a Bright New World*, The Age, Mar. 21, 1991, p. 23.

35. Crompton, T.R. (1990) *Battery Reference Book*, Butterworths, London.

36. Appleby, A.J. and Foulkes, F.R. (1989) *Fuel Cell Handbook*, Van Nostrand Reinhold, N.Y., 1989.

37. Anon. (1986) *New Scientist*, July 17, 1986, pp. 34-39.

38. Henriksen, G.L., DeLuca, W.H. and Vissers, D.R. (1994) *Chemtech* November 1994, pp. 32-38.

39. Lennon, A. (1994) *BYTE* March 1994 19, pp. 156-181.

40. Siegler, R. (1989) *WNIE*, Oct. 1989, pp. 20-22.

41. SAFT Corporation, Lithium Series *LC, LCP, LS, LM & LX Cells and Batteries* (brochure) New York, US.

42. Bockris, J. O'M. and Appleby, A.J. (1986) *Energy 11*, p. 95.

43. Anon. (1987) *New Scientist*, July 23, 1987, p. 31.

44. Anon. (1987) *New Scientist*, Nov. 19, 1987, p. 38.

45. Rudd, E.J. (1989) *Electric Vehicle Developments 8*, pp. 53-54.

46. Marsh, C. and Licht, S. (1994) *Journal of the Electrochemical Society* **141**, pp. L61-L63.

47. Harris, F.M. and Schimpf, M.J. (1994) *Proceedings of 9th Annual Battery Conference on Applications and Advances*, pp. 146-151.

48. Anon. (1995) *Newsbytes News Network*, May 2, 1995. See also company brochure.

49. Alupower Canada Ltd. (1990) *News from Alupower*, private communication with J. Stannard, File S640, Sept. 12, 1990.

50. Hooton, E.R. and Munson, K. (Eds.) (1995) *Jane's Battlefield Surveillance 1994-1995*, Jane's Information Group, Surrey, p. 236.

51. Anon. (1989) *Aerospace Daily* **152**, Dec. 26 1989, pp. 475-476.

52. Seemann, G.R. and Harris, G.L. (1981) *RPVs Remotely Piloted Vehicles*, Second International Conference, Bristol UK, 1981, Supplementary Papers, p. 12.1.

53. Hodges, J.N., Cameron, K., Brown, R.D. and Feik, R.A. (1980), *Ch. 1 Aerodynamics* in Vol. 4, Technical Report WSRL-0111-TR, Weapons Systems Research Laboratory, DSTO Salisbury, S.A. (Confidential).

54. Taylor, J.W.R. (ed). (1988) *Jane's All the World's Aircraft 1987-88*, Jane's Publishing Co., London, pp. 816 & 837.

55. Vandersteen, A.D. (1987) *IEEE AES Magazine*, June 1987, pp. 24-30.

56. Anon. (1988) *Aviation Week and Space Technology*, Aug. 22, 1988, p. 93.

57. Anon. (1990) *Interavia Air Letter*, Feb. 28, 1990, p. 3.

58. Doyle, J.J. (1988) *RPVs Remotely Piloted Vehicles*, Seventh International Conference, Bristol UK, Sept. 12-14, 1988, Supplementary Papers, p. K6.1.

59. Sagi, A. (1985) *RPVs Remotely Piloted Vehicles*, Fifth International Conference, Bristol UK, 9-11 Sept 1985, p. 9.1.

60. Taylor, D.R. (1988) *RPVs Remotely Piloted Vehicles*, Seventh International Conference, Bristol UK, 12-14 Sept., 1988, p. 25.1.

61. Farrell, J.L. (1976) *Integrated Aircraft Navigation*, Academic Press, N.Y., p. 14.

62. Draper, C.S., Wrigley, W. and Hovorka, J. (1960) *Inertial Guidance*, Pergamon Press, N.Y., Ch. 1.

63. Mant, I.S. (1982) *RPVs Remotely Piloted Vehicles*, Third International Conference, Bristol UK, 13-15 Sept., 1982, Supplementary Papers, p. 26.1.

64. Sweetman, B. (1990) *International Defense Review 7/1990*, pp. 773-6.

65. Newman, L. (1976) *Bicentennial National Aerospace Symposium on New Frontiers in Aerospace Navigation*, 27-28 April, 1976, pp. 48-51.

66. Kayton, M. and Fried, W.R. (Eds.) (1969) *Avionics Navigation Systems*, John Wiley & Sons, N.Y., p. 7.

67. Heron, I. et al. (1987), The Technical Cooperation Program, TTCP Subgroup W, *Technical Panel WTP-5*, Vol. 1, 1987, p. 26.

68. Cooper, I.F. and Birkenshaw, J.A. (1981) *RPVs Remotely Piloted Vehicles*, Second International Conference, Bristol UK, p. 16.1.

69. Boyle, D. (1989) *International Defense Review 5/1989*, pp. 607-610.

70. Anon. (1994) *Global Positioning & Navigation News* 12, June 6,1994,

71. Anon. (1990) *UK steals lead in rich race for car navigation, The Australian-Computers & High Technology*, Dec. 4, 1990, p. 45.

72. Anon. (1991) *Navigating by Wogan, Electronics World + Wireless World*, Jan. 1991, p. 13.

73. Duffet-Smith, P. and Woan, G. (1992) *Journal Of Navigation* 45, pp. 157-165.

74. Hewish, M. (1994) *International Defence Review 4/1994*, pp. 49-55.

75. Anon. (1994) *Global Positioning System, Aviation Daily* 315, Mar. 14 1994, p. 405.

76. Hartz, W.G., Alexovich, R.E. & Neustadter, M.S. (1989) *NASA Contractor Report No. 4263*.

77. Wilson, R. (1990) *Computer Design*, April 1, 1990, p. 42.

78. Iversen, O. (1990) *Australian Macworld*, Sept. 1990, pp. 103-104.

79. Iversen, O. (1990) *Australian Macworld*, Aug. 1990, pp. 77-78.

80. Iversen, O. (1990) *Australian Macworld*, Oct. 1990, pp. 215-223.

81. Walmsley, N.P., Skodras, A.N. and Curtis, K.M. (1994), *IEEE Transactions on Consumer Electronics* **40**, pp. 11-19.

82. Barnsley, M.F. and Sloan, A.D. (1988) *Byte*, Jan. 1988, pp. 215-223.

83. Wood, K. (1990) *Electronics World + Wireless World*, Aug. 1990, pp. 703-708.

84. Barnsley, M.F. (1988) *Fractals Everywhere*, Academic Press, San Diego, Ca.

85. Koornwinder, T. (Ed.) (1993) *Wavelets: an elementary treatment of theory and applications*, World Scientific, River Edge, NJ.

86. Rinaldo, R. and Calvagno, G. (1994) *Proceedings- IEEE International Symposium on Circuits and Systems* **3**, pp. 113-116.

87. Cohen, A.M. and Resnikoff, H.L. (1994) *Proceedings of SPIE- The International Society for Optical Engineering* **2298**, pp. 304-315.

88. Fisher, Y. (1994) *Fractals* **2**, pp. 347-361.

89. Fisher, Y. (1994) *Fractal Compression: Theory and Application to Digital Images*, Springer-Verlag, New York.

90. Jacquin, A.E. (1990) *Proceedings IEEE Conference on Acoustics, Speech and Signal Processing* **4**, pp. 2225-2228.

91. Barnsley, M. and Hurd, L. (1992), *Fractal Image Compression*, AK Peters Ltd, Wellesley, Ma.

92. Fisher, Y. (1994) *Fractal Compression: Theory and Application to Digital Images*, Springer-Verlag, New York.

93. Monro, D.M. and Dudbridge, F. (1995) *IEEE Computer Graphics and Applications* **15**, pp. 32-41.

94. Bani-Eqbal, B. (1995) *IEE Colloquium Fractals and Image Processing* (Digest No. 1995/006), pp. 2/1-2/3.

95. Baker, C. & Leopold, G. (1991) *Defense News*, Mar. 18, 1991, pp. 20-30.

Portable Unmanned Aircraft System Concept Investigation

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16. *ABSTRACT*
This report investigates the feasibility of a portable unmanned aircraft system (PUMA) for deployment in various close range (up to 30 km) reconnaissance and surveillance missions, which would provide a capability, estimated to be 50 to 60% of the performance of much larger and significantly more expensive sytems. The PUMA would have a total mass of 10-12 kg and a 3 kg electrically powered flying wing configuration, which could be launched by a rubber bungee and captured by either a net or a special arrestor. The primary sensor would be a charge coupled device camera with either a second or third generation image intensifier. Navigation and control of the vehicle could be performed by an inexpensive attitude and heading reference system combined with a small global positioning system receiver. Data would be transmitted over very high frequency channels, which could be accomplished by employing data compression techniques.

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